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vol. 2

19TH INTERNATIONAL COSMIC RAY CONFERENCE

LA JOLLA, USA   AUGUST 11-23, 1985

CONFERENCE PROGRAM SESSIONS VOL. 2

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CONFERENCE PAPERS

OG

SESSIONS
VOL. 2

PREFACE

The 19th International Cosmic Ray Conference, under the auspices of the Cosmic Ray Commission of the International Union of Pure and Applied Physics, is being held on the campus of the University of California, San Diego, on 11 through 23 August 1985. In keeping with the tradition begun in 1971 by the Australian organisers of the 12th ICRC, the Proceedings of this conference are appearing in two sets of volumes. The first set, consisting of volumes 1 through 8, is being distributed to all participants at the beginning of the conference. This set contains the contributed papers. The second set, distributed after the conference, contains invited, rapporteur, and highlight papers. The papers are reproduced here exactly as they were received from the authors, without refereeing.

For the 19th ICRC, the scientific program was organized according to three major divisions— OG (cosmic rays and gamma rays of Galactic Origin), SH (Solar and Heliosphere), and HE (High Energy). Technical papers are included in each of the three divisions.

This conference depended on funds from several agencies of the United States government, including major financial support from the National Aeronautics and Space Administration and support from the National Science Foundation, the Department of Energy, and the Air Force Geophysics Laboratory. Important financial support also came from the Center for Astrophysics and Space Sciences of the University of California, San Diego, from the California Space Institute of the University of California, from the Department of Physics and Astronomy of the University of Maryland, College park, from the International Union for Pure and Applied Physics, and from several corporate sponsors who will be acknowledged by name in the post-conference volumes.

We appreciate the confidence placed in the conference organisers by the Cosmic Ray Commission, and acknowledge with thanks the role of the Commission members in setting up the rules for the conference and in advising the organisers during its planning.

We are grateful to all of the members of the various organising committees listed at the front of this volume. The three Program Committees went to great effort to organise a coherent scientific program and to schedule four parallel sessions with a minimum of conflicts. The Local Organising Committee has worked long and hard to ensure efficient and hospitable accommodations for all the participants, both in the scientific sessions and outside them. The Publications Committee not only took great pains to assemble these volumes but also maintained an orderly data base of papers and authors which was extremely helpful to the program committees. The General Organising Committee made important contributions of ideas and efforts to make the conference possible; this committee included international representation from all of North America, thus the departure from the traditional name of National Organising Committee. And the entire effort was coordinated by the dedicated members of the Steering Committee.

Martin H. Israel, Chairman   August, 1985
General Organising Committee

LETTER FROM THE EDITORS

This conference marks a departure from previous conferences in this series in that the publication of the Conference Papers was carried out an entire continent away from the activities of Local Organizing Committee. This posed some problems but, to the considerable surprise of the Publications Committee members, the one that was expected to be the most trouble turned out not to be significant. The overwhelming majority of those submitting papers and abstracts sent them to the correct address, not to La Jolla as was feared. We wish to thank our many authors for their alertness and commend them for handling a complicated situation so well.

There are eight volumes to be distributed to the conference participants in addition to the Conference Program and Author Index: three volumes for OG, two for SH and three for HE. the detailed makeup of these volumes is described in the prefaces written by the Scientific Program chairmen for their respective volumes. Out of some 1100 abstracts that were accepted by the Scientific Program Committees for inclusion in the conference some 929 papers were finally received in time for inclusion in the Conference Papers. This represents a response of approximately 84 percent, a modest improvement. Even if one excludes the 42 one page papers that should be considered as 'confirming abstracts', even though there was no such formal category, the response was somewhat higher than that of recent years. We attribute this to the carrot of a later deadline than before coupled with the stick of there being no printing of post deadline contributed papers. We believe that this decision of the General Organizing Committee was a wise one. Of course invited, rapporteur, and highlight talks will be printed in volumes to be distributed to the participants after the conference as usual.

The Publications Committee had much generous help in performing its duties: from Goddard Space Flight Center we had the help of B. Glasser, L. Harris, E. Schronce, N. Smith, J. Esposito and T. Smith. From the Naval Research Laboratory we were helped by T. Mazzotta, and at the University of Maryland M. L. Snidow and J. Mucha gave much needed assistance. Special thanks are due to Caryl Short, the lone staff member of the Publications Committee. She maintained the computer data base, organized the abstracts as they arrived, and kept track of the papers themselves to see that the finally arrived in the right place at the right time. Without her help the job would have been far more difficult than it was.

PUBLICATIONS COMMITTEE   August, 1985

Frank C. Jones, Chm.
Jim Adams
Glen M. Mason

OG SESSIONS
VOLUME II

Preface to the OG Volumes

The contributed papers presented at the 19th International Cosmic Ray Conference were arranged into three major divisions: OG (for cosmic ray and γ-ray Origin and Galactic phenomena); SH (for Solar and Heliospheric phenomena); and HE (for High Energy phenomena). The OG division encompasses topics related to the origin of galactic cosmic rays and γ-rays, the nature and distribution of their sources, and their interactions with galactic fields and matter. Contributed papers for OG sessions were organized under the following headings:

OG1 γ-ray Bursts
OG2 γ-rays from Point Sources
OG3 Diffuse γ-ray Emission
OG4 Cosmic Ray Nuclei with <1 TeV (Composition, Spectra, and Anisotropy)
OG5 Cosmic Ray Nuclei with >1 TeV (Composition, Spectra, and Anisotropy)
OG6 Electrons, Positrons, and Antiprotons
OG7 Interstellar Propagation and Nuclear Interactions
OG8 Cosmic Ray Sources and Acceleration
OG9 Techniques and Instrumentation

Note that the present OG division is broader than in the past; it includes papers from both the OG and XG divisions at previous International Cosmic Ray Conferences, as well as many papers previously in the T division.

Approximately 400 preliminary abstracts were received under the OG headings listed above. These were organized into 32 contributed paper sessions for purposes of oral presentation. Papers and confirming abstracts for OG papers are contained in Volumes 1, 2, and 3 of these Proceedings. Volume 1 contains papers under headings OG1, OG2, and OG3; Volume 2 contains OG4, OG5, and OG6; while OG7, OG8, and OG9 are contained in Volume 3. Papers on topics of related interest appear in the SH proceedings (Volumes 4 and 5) and the HE proceedings (Volumes 6, 7, and 8).

Four rapporteur speakers were invited to review the OG contributed paper sessions and report on new results and developments, areas of controversy, and future research directions. The written versions of these papers will appear in a later volume of these proceedings, along with other invited papers.

I wish to thank the other members of the OG Program Committee for their help in defining the OG topics, in reading the abstracts and organizing the sessions, and for their advice on the selection of rapporteur, highlight, and invited speakers. Members of the committee include: G. L. Cassiday, Jr. (University of Utah); C. E. Fichtel and A. K. Harding (Goddard Space Flight Center); R. E. Lingenfelter and J. L. Matteson (University of California at San Diego); D. Muller (University of Chicago); and W. R. Webber (University of New Hampshire).

Richard A. Mewaldt
Chairman, OG Program Committee

This conference is the 19th in a series. Previous conferences in this series were held at:

Cracow, Poland	-	1947
Como, Italy	-	1949
Bagneres-de-Bigorre, France	-	1953
Guanjuato, Mexico	-	1955
Varenna, Italy	-	1957
Moscow, USSR	-	1959
Kyoto, Japan	-	1961
Jaipur, India	-	1963
London, UK	-	1965
Calgary, Canada	-	1967
Budapest, Hungary	-	1969
Hobart, Australia	-	1971
Denver, USA	-	1973
Munchen, FRG	-	1975
Plovdiv, Bulgaria	-	1977
Kyoto, Japan	-	1979
Paris, France	-	1981
Bangalore, India	-	1983

OG 4.3
COSMIC-RAY ISOTOPES

OG 4.4
OBSERVATIONS OF ULTRA HEAVY COSMIC-RAY NUCLEI

OG 5.2
COSMIC RAYS ABOVE 1 TEV: COMPOSITION

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COSMIC-RAY ANISOTROPY

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ORIGIN OF ULTRA-HIGH-ENERGY COSMIC RAYS

OG 6.1
ANTI-PROTONS AND RELATED SUBJECTS

OG 6.2
ELECTRONS, POSITRONS, AND RADIO
MEASUREMENTS OF SYNCHROTRON RADIATION

Absolute Rigidity Spectrum of Protons and Helium Nuclei Above 10 GV/c

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Abstract

Proton and helium nuclei differential spectra were gathered with a balloon borne magnet spectrometer. The data were fitted to the assumption that the differential flux can be represented by a power law in rigidity.   In the rigidity range 10-25 GV/c the spectral indices were found to be $-(2.74 \pm 0.04)$ for protons and $-(2.71 \pm 0.05)$ for helium nuclei.

1. Introduction.   The absolute rigiditiy spectra of · protons and Helium nuclei have become particularly important due to the recent measurements of secondaries of these particles.   The recent publication of the absolute e- spectrum necessitated a very careful analysis of the detection efficiencies and sensitivities of the New Mexico State University magnetic spectrometer. The maximum detectable momentum for the 1976 flight (reported here) was 80 GV/c.   During the analysis, it was found that magnet spectrometer measurements in general are subject to systematic errors that affect the spectral index but not the absolute flux at low energies. In this paper we present a brief discussion of the systematic errors, and spectral indices for protons and helium nuclei in the rigidity range 10-25 GV/c. Absolute fluxes will be presented at the conference.

2. Data Analysis.   The apparatus is described in detail in references (1) and (2).   It was comprised of (top to bottom): a gas Cherenkov counter (G) with a proton Cherenkov threshold of 40 GV/c (rigidity); two plastic scintillators (S1 and S2); 8 multiwire proportional counters (MWPC); and a lead-scintillator shower counter consisting of 7 layers each containing 1 radiation length of lead (P1-P7).   The MWPC provide 8 readouts on the x axis (axis of bending) and 4 readouts on the (orthogonal) y axis. All phototubes were pulse-height analyzed.   Data readout was initiated for all occurences of an S1*P1*P7 and/or an S1*P1*P7*G coincidence.   The geometric factor of the instrument was 324 ± 5 cm^2-str and the live-time fraction was 0.80.   The data were

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gathered on a balloon flight from Palestine, Texas on May 20, 1976. The data gathering period lasted 6.4×10^4 seconds at an average altitude of 5.8 gm*cm^-2. Data for the spectral analysis were selected from the flight tapes by requiring the following:

(1) The charge of the particle (as determined from S1 and S2) correspond to 0.0-1.8 charge units for protons or 1.8-2.7 charge units for helium.
(2) All MWPC readouts be valid and that the measured trajectory fit to a continuous track with a chi-square of 30 in the x axis, and 8 in the y axis.

Failure of particles to pass the above criteria was dominated by criterion 2. Each MWPC is only about 90% efficient. The measured efficiency for passing criterion 2 was 33% for protons and 24% for helium nuclei.

3. Results. Figures 1a and 1b show the proton and helium data gathered during the flight. The plots show number of events vs magnetic deflection (1/magnetic rigidity), measured in c/GV. The central part (deflection = 0) of each plot represents the highest rigidities. Moving toward the right corresponds to lower rigidities. The decline in number of particles to the right of 0.12 c/GV is due to the combined effects of solar modulation and the geomagnetic cutoff.

The data in Figure 1 have been analyzed by fitting them to the assumption that the differential flux is a power law in rigidity. Other factors which enter the fit are: the resolution function of the instrument, solar modulation, and the exact location of the zero-deflection point. The zero-deflection point in Figure 1 was determined by operating the instrument with the magnet off just prior to the flight. The center of the deflection distribution gathered with the magnet off is taken as the zero-deflection point, and the distribution of deflections is taken as the resolution function for the instrument. Figure 2 shows the resolution function.
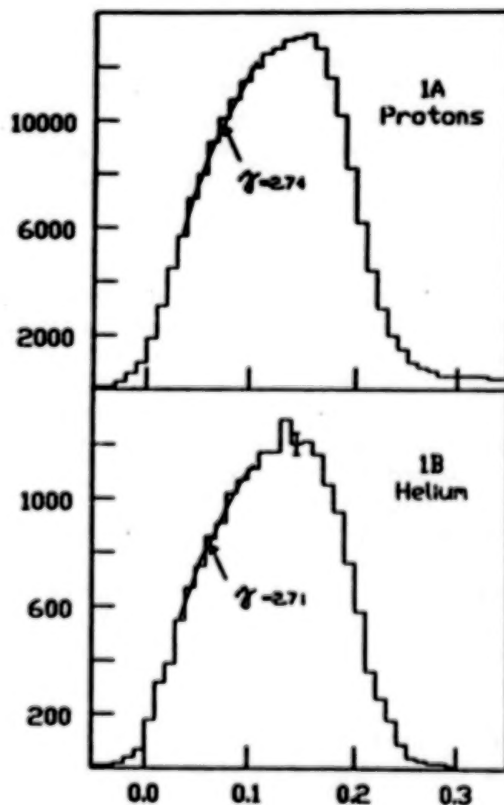
Figure 1. Deflection spectra

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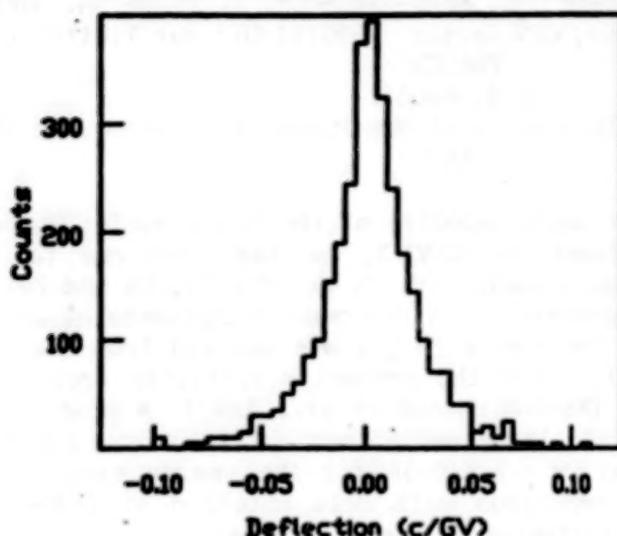
Figure 2
Resolution
Function

One of the most serious sources of possible systematic error for spectral indices is a change in the zero-deflection point between the calibration and the flight. It was hoped to turn the magnet off at the end of the flight for another calibration, but the instrument operation ended abruptly due to battery failure and the calibration was not performed. A cross-check was made however, by using the 8-on protons and helium gathered during the flight. These two samples were fit assuming the proton Cherenkov threshold of 40 GV/c (helium threshold of 80 GV/c). Since the Cherenkov thresholds are near the upper limit of the instrument to resolve the deflection, the dominant factor in the fits was the offset of the zero-deflection point. The offset was determined to be -(0.002±0.002) c/GV. In order to minimize the effects of the offset error, solar modulation and possible changes in the resolution function, we limit our analyses to the deflection range 0.1-0.04 c/GV (10-25 GV/c rigidity). Further, we have used a solar modulation of 600 MeV, which was determined using the data below 10 GV/c. Under these circumstances we find $\gamma = -(2.74\pm0.04)$ for protons and $-(2.71\pm0.05)$ for helium nuclei. The uncertainty in the proton spectral index is dominated by the offset uncertainty, and statistics dominates the uncertainty for helium nuclei.

References

(1) Golden, R. L. et al. (1978), Nuc. Instr. and Meth. 148, 179.
(2) Golden, R. L. et al. (1984), Ap. J. 287, 622.

SOURCE SPECTRAL INDEX OF HEAVY COSMIC RAY NUCLEI

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1. Introduction. From the energy spectra of the heavy nuclei observed by the French-Danish experiment on HEAO-3, we have derived the source spectra of the mostly primary nuclei (C, O, Ne, Mg, Si, Ca and Fe) in the framework of an energy dependent leaky box model (Engelmann et al. 1985). The energy dependence of the escape length was derived from the observed B/C and sub-iron/iron ratios and the presently available cross sections for C and Fe on H nuclei (Koch-Miramond et al., 1983). A good fit to the source energy spectra of all these nuclei was obtained by a power law in momentum with an exponent γ =-2.4+0.05 for the energy range 1-25GeV/n (Engelmann et al. 85). Comparison with data obtained at higher energy suggested a progressive flattening of these spectra.

In the present paper we want to derive more accurate spectral indices by using better values of the escape length based on the latest cross section measurements (Webber 1984, Soutoul et al. this conference). Our aim is also to extend the analysis to lower energies down to 0.4GeV/n (kinetic energy observed near earth), using data obtained by other groups. The only nuclei for which we have a good data base in a broad range of energies are O and Fe , so the present study is restricted to these two elements.

2. Derivation of the source spectra. We work along the same lines as in Engelmann et al. 1985. We first derive the interstellar spectrum by "demodulating" the observed spectrum, using the "force field approximation" (Gleeson and Axford, 1968) ; then we correct the demodulated flux values for the nuclei of secondary origin produced the interstellar medium and for the energy loss suffered by the particles during their propagation. We get the interstellar flux of the "surviving" primaries J(E), which is related to the source strength dQ/dE by the relationship :

$$\frac{dQ}{dE} \propto J(E)\left(\frac{1}{\lambda_{di}} + \frac{1}{\lambda_e (E)}\right) - \frac{\partial}{\partial E}\left[J(E)\frac{dE}{dx}\right] \qquad (1)$$

where λ_{di} is the pathlength for nuclear destruction of the element i in the interstellar medium and λ_e is the escape length, the value of which is derived in a companion paper (Soutoul et al., 1985). $\partial / \partial E$ is the ionization energy loss term and dE/dx is the stopping power of the particle in pure H.

When applying this step by step procedure, we are faced with two difficulties : i) if the modulation correction is too large, the uncertainty on its value will lead to a large uncertainty in the interstellar flux value. To keep this kind of error at a relatively low level, we select among the published data those registered in such conditions (energy range, modulation level) that the modulation

correction on the flux values does not exceed 35%. When this condition is fulfilled an error of 0.10 GV on the modulation parameter around a mean value of 0.40GV leads to a maximum error of 10% on the flux value corrected for modulation.   ii) For the flux value registered by a particular experiment at a given energy, there are two major causes of errors : the statistical error and a systematic error due to the uncertainties on the exposure factor of the instrument and on the atmospheric corrections for balloon experiments. If we renormalize the data in order to put certain flux values from different experimenters in agreement we introduce a subjective feeling in the choice of these flux values. To avoid this problem we do not try to derive from the data the absolute flux values but merely the spectral indices measured by each experimenter in given energy ranges.

3. Data base used in this study.   Our data base is listed in Table I

Reference	Date of measurement	Mont Washington neutron monitor count rate	Modulation parameter ϕ GV	Type of particle	Selected energy range
Webber 85[1]	1974, July	2290	0.50	0,Fe	0.95-6
Webber 85[1]	1977, Sept.	2360	0.35	0,Fe	0.65-6
Webber 85[1]	1974,77,78	2300	0.50	0,Fe	10.5-112
HEAO-3[2]	1979 Oct. to 1980 June	2190	0.60	0,Fe	1.3-25
Juliusson 74	1971-72 Sept	2350	0.40	0	23-76
Orth & al.78	1972 Sept	2350	0.40	0,Fe	2.4-11
Maehl & al77	1973 Aug.	2350	0.40	0,Fe	0.85-2.25
Caldwell 77	1974 Sept	2310	0.50	0	5.5-95
Minagawa 81	1975 Sept	2404	0.30	Fe	1.5-8.0
Simon & al80	1976 Oct.	2420	0.30	0,Fe	2.5-630

(1) These data consist of revisited flux values obtained in several balloon flights and published in Lezniak and Webber 1978 and Webber 1983. More accurate atmospheric corrections have been applied.
(2) Juliusson et al., 1983 ; Engelmann et al., 1985.

The modulation parameter ϕ characterising the conditions prevailing at the time of each experiment can be correlated to the counting rate of the Washington neutron monitor (Lockwood and Webber 1979, 1981).
The interstellar energy spectra dJ/dE of O and Fe derived from these selected data after demodulation have been plotted in Fig. 1 as a function of the momentum of the particle.

4. Results.   As can be seen in Fig. 1, the differences between the experimental points obtained at the same energy are much larger than the errors quoted by the authors. As mentioned above this is probably due to errors on the geometry and efficiency of the experiments and on the atmospheric corrections. So we consider separately each experiment, and for some of them we devide the energy range they cover into several energy intervals. For each experiment and energy domain we derive the spectral index γ of the source strength assumed to follow the law :
$$dQ/dE = KP^{-\gamma}\qquad(2)$$
where P is the momentum of the particle in GeV/c/n. The values of the γ index for O and Fe have been plotted as a function of momentum in

Fig.2 and 3 respectively.

For O the data seem to be consistent with a constant γ index above 4GeV/c/n with a weighted mean value γ_o=2.29+0.03 (Note that the HEAO results are significantly above the average ; excluding these data would lead to a weighted mean γ_o=2.22+0.04). Below 4GeV/c/n, the index seems to increase when the momentum decreases, up to $\gamma_o \simeq 2.9$ at 1.5GeV/c/n. For Fe we find for the weighted mean a value of γ_{Fe}=2.36+0.05 which is nearly the same as that found for O at high energy. But the increase observed for O at low energy does not seem present for Fe, although the large error bars and the scarcity of the points at low energy prevent us from drawing any definite conclusion.

The quoted errors on γ are due to the errors on the flux values and to the spread of the corresponding points. If we include in addition the error on λ_e due to cross section errors on the production of B by spallation of heavier nuclei and of Fe secondaries by spallation of Fe, we get the final values λ_o(H.E.)=2.29+0.06 and λ_{Fe}=2.36+0.07. Therefore a unique power law in momentum does not hold for the O source spectrum. What about a power law in total energy, which we have used earlier (Perron et al., 1981)?:

$$dQ/dE_{Tot} = K' E^{-\gamma'} \qquad (3)$$

The γ' index values from the experimental data have been plotted as a function of the kinetic energy for O nuclei in Fig. 4. The weighted mean γ value above 3 GeV/n is again 2.29+0.03 and the same type of increase is observed when going towards lower energies.

It is worthwhile to stress that this type of increase cannot be due to an error in the modulation correction (unless the modulation theory is grossly in error). An error of +0.1GV around an average value of 0.4GV for the modulation parameter would lead to an error of +0.07 on the spectral index around 1GeV/n, i.e. about 10 times less than the index variation observed between 1 and 3GeV/n (interstellar kinetic energy).

4. Conclusion. We find, at least for O nuclei an apparent increase of the γ index of the source spectrum below 3GeV/n. Is this low energy steepening of the spectrum real ? As discussed above, the careful selection of the data used in this study should prevent the demodulation to be responsible for this result. As concerns the partial cross sections from which the escape length is derived, the uncertainty in their values may introduce an error on the source abundances. If some energy dependences were left on the cross section errors, these would propagate into an error on the source spectral index. It is precisely in the energy region where the γ index is changing (0.8 to 3GeV/n) that the cross sections were measured with the best accuracy (Webber,1984). From the quoted errors, we calculate that a possible energy dependence on σ could be responsible at maximum for an apparent slope of 0.05, far smaller than the observed γ variation.

This apparent increase of the source spectrum at low energy can be brought together with the flattening of the CNO source spectrum observed in the TeV energy region (Engelmann et al. 1985). It is in agreement with our suggestion that a soft component with a source spectral index around 2.7 may be superposed on a common source spectrum, including H and He, with a spectral index $\gamma \simeq 2.1$. In the few GeV/range, both components would contribute to the observed flux of heavies, leading to a spectral index around 2.3 .
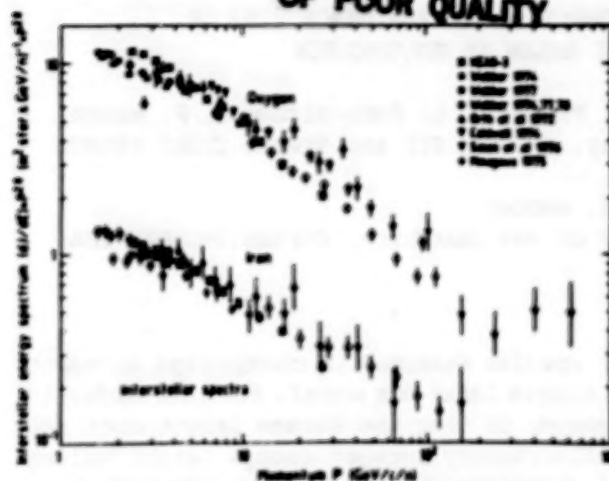
Fig. 1 : Near-earth interstellar spectra of O and Fe nuclei, derived from experimental data corrected for the effect of solar modulation. The differential energy flux values have been plotted as a function of the momentum P. The spectra have been "flattened" by multiplication by $P^{2.6}$.
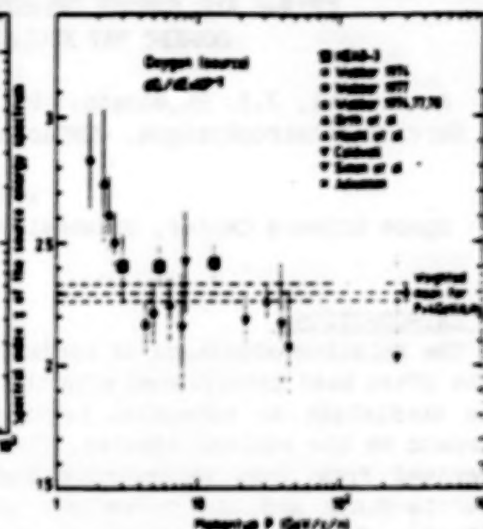
Fig. 2 : Oxygen source spectral index γ plotted as a function of momentum P, assuming for the spectral shape a power law in momentum.
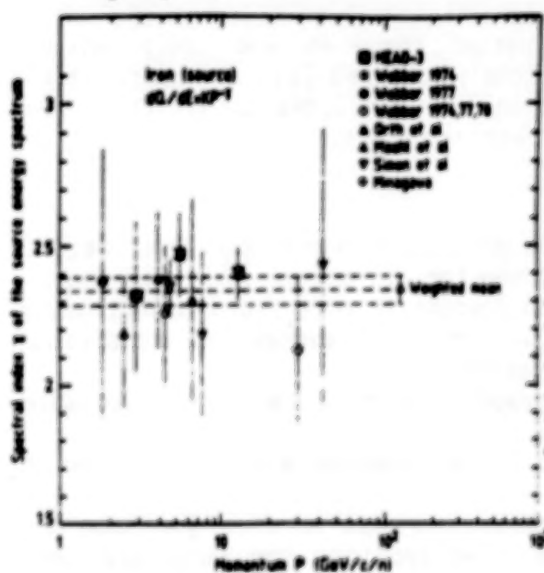
Fig. 3 : Iron source spectral index plotted as a function of momentum, assuming for the spectral shape a power law in momentum.
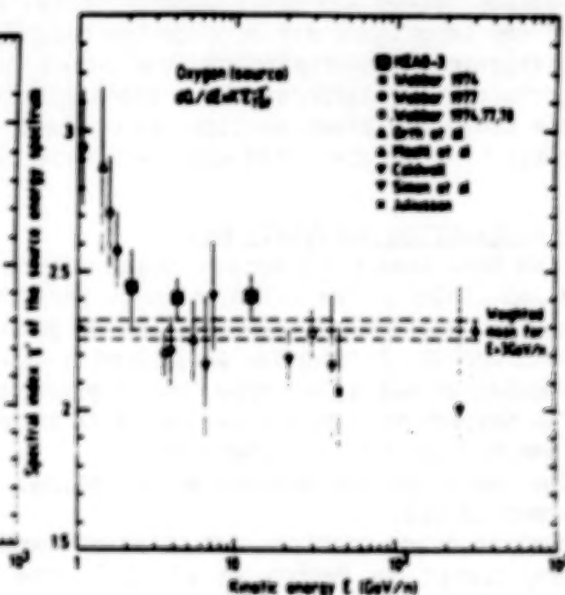
Fig. 4 : Oxygen source spectral index γ plotted as a function of kinetic energy, assuming for the spectral shape a power law in total energy.

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CHARGE AND ENERGY DEPENDENCE OF THE RESIDENCE TIME OF
COSMIC RAY NUCLEI BELOW 15 GEV/NUCLEON

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1 INTRODUCTION.

The relative abundance of nuclear species measured in cosmic rays at earth
has often been interpreted with the simple leaky box model. For this model to
be consistent an essential requirement is that the escape length does not
depend on the nuclear species. The discrepancy between escape length values
derived from iron secondaries and from the B/C ratio was identified by
Garcia-Munoz and his co-workers using a large amount of experimental data
[7-10]. Ormes and Protheroe found a similar trend in the HEAO data although
they questioned its significance against uncertainties [9]. They also showed
that the change in the B/C ratio values implies a decrease of the residence
time of cosmic rays at low energies in conflict with the diffusive convective
picture [11-12]. These conclusions crucially depend on the partial cross
section values and their uncertainties. Recently new accurate cross sections
of key importance for propagation calculations have been measured [6] Their
statistical uncertainties are often better than 4% and their values
significantly different from those previously accepted [6]. In this paper we
use these new cross sections to compare the observed B/C+O and (Sc to Cr)/Fe
ratio to those predicted with the simple leaky box model.

2 PROPAGATION CALCULATIONS.

We have used the Comstock computer code previously used by Koch et al,Perron
et al.[1-2-3]. The calculation is performed for the simple leaky box model,
with an exponential distribution of path lengths in pure hydrogen and takes
into account β-decay for long lived species,ionisation energy losses and solar
modulation using the force field approximation [4].
The neglect of interstellar helium in propagation calculations is questionable
(see OG 7.2-11 this conference).
The input source spectra are identical for all species with a power law in
momentum [5].
Nuclear cross sections are based on experimental data wherever possible and
are listed in Perron et al. [2]. The cross sections for boron and iron
secondaries are those measured by Webber [6]. We otherwise use Silberberg and
Tsao's formulae [19].
The computer code uses a stepwise procedure to solve the set of first order
differential equations. In the energy and charge range of this paper the
energy loss term cannot be neglected and we have checked that it is accurately
calculated.

3 RESULTS.

Above 1 GeV/n and at low energies we analyse satellite data which are free
from atmospheric effects and have high statistical accuracy [7-8]. At
intermediate energies we analyse balloon data as well [13-14-15-16-17-18].
The experimental data for the B/C+O ratio are shown in figure 1. This ratio was

chosen because it is relatively insensitive to possible small differences between observed and computed C/O ratio throughout the whole energy range [5]. Also we adjust the source abundances especially those of the main progenitors of boron so that their calculated abundances are close enough to their observed values.

We first compare the calculation to the HEAO B/C+O data. The deceleration parameter appropriate for these data is taken equal to 600MV [5]. We try values of the mean escape length varying with energy according to:

(1) $\lambda_{esc}=\lambda b \cdot \beta \cdot R^{-\delta}$ $R > 5.5GV$
    $\lambda_{esc}=\lambda b \cdot \beta \cdot 5.5^{-\delta}$ $R < 5.5GV$

where R and β are the interstellar values of the rigidity and the velocity relative to that of light.

We find that $\lambda b=24.0$ g/cm^2 and $\delta=.65$ provide a reasonably good agreement in the HEAO energy range (see figure1).

Then we perform a set of propagation calculations with a grid of slightly different values of λb around its nominal value. From this we can derive the values of λ_{esc} which precisely yield all the observed B/C+O values and their statistical uncertainties as well (figure 3).

This procedure is repeated for the (Sc to Cr)/Fe ratio with trial functions:

(2) $\lambda_{esc}=\lambda f \cdot \beta \cdot (1+.4/Ekin) \cdot R^{-\delta}$ $R > 5.5GV$
     $\lambda_{esc}=\lambda f \cdot \beta \cdot (1+.4/Ekin) \cdot 5.5^{-\delta}$ $R < 5.5GV$

where Ekin is the interstellar kinetic energy in GeV/n. The term in parenthesis takes conveniently care of a steepening that is not present in the B/C+O data. Good agreement with the data is found for $\lambda f=26.8$ g/cm^2 and $\delta=.65$ (see figure2). From a set of propagation calculations with different λf we derive the λ_{esc} values yielding each experimental point (figure 3).

We then compare the B/C+O ratio calculated with (1) to the low energy data. For this ratio the calculation is dependent on the adopted solar modulation level. Figure 1 shows the calculated curves for 490MV and 350MV [7] (See also OG 4.1-2 this conference). We also wish to check the sensitivity of these results to the adopted β dependence in (1) (constant residence time below 5.5GV). The ratio calculated with a mean escape length independent of energy and equal to 7 g/cm^2 is plotted on figure 1 for the same levels of modulation as above.

For the (Sc to Cr)/Fe the low energy results of calculations with constant escape length are shown on figure 2. Three distinct values are considered: 7g/cm^2, which is appropriate for comparison to the low energy B/C+O data; 11g/cm^2 consistent with that found around 2GeV/n and finally an infinite escape length corresponding to complete confinement.

4 DISCUSSION.

The abundance ratio calculated with (1) and (2) and a deceleration parameter of 600MV agree reasonably well with the HEAO data (figure 1 and 2).

Perron et al. have suggested that these data are consistent with larger values of δ than previously calculated from balloon data [2]. Further calculations showed that even larger values of δ would provide a better fit [3-9]. Our adopted value of δ is in agrement with these results. The flattening in λ_{esc} for boron is not observed for iron secondaries, in the HEAO data (see figure 3).This difference could be even more marked below 1GeV/n although large statistical uncertainties of the (Sc to Cr)/Fe ratio in balloon data do not allow to draw firm conclusions. Interestingly enough the low energy satellite

data and the HEAO data around 1 GeV/n are consistent with the same value of
λ_{esc} within uncertainties for iron secondaries (see figure 2).
At low energies the dependence of the escape length with energy from the B/C+O
ratio is less than previously reported [7-9-10]. Indeed if a modulation level
as low as 350MV is adopted a constant grammage(7 g/cm²) would keep agreement
with the B/C+O data,whereas for a larger modulation level a constant
residence time would agree better.
The values of λ_{esc} yielding the experimental HEAO ratio are shown in figure 3
together with those calculated from (1) and (2). The differences between the
escape length values derived from iron secondaries and from boron are
statistically significant especially below 4 GeV/n. They are larger than
those reported by Koch   et al. and similar to those from Ormes and Protheroe
[3-9]. At low energies, calculations with the escape length from B/C+O ratio
underestimate iron secondaries by a large factor (see figure 2). Above 1GeV
the (Sc to Cr)/Fe ratio predicted from (1) is also plotted on figure2. The
underestimate of this ratio resulting from the use of (1) could be accounted
for by a 5% overestimate of partial cross sections for boron and an
underestimate of similar amount for those of subiron secondaries. Systematic
errors can be generated by the calculation of cross sections. Partial cross
sections from iron have been accurately measured at several energies below
2GeV/n and show a rather steep and quite consistent energy dependence [6].
Starting from this grid the program calculates the cross sections at all other
energies.We estimate that for reasonably smooth interpolation , possible
systematic errors on the calculated ratio below 2 GeV/n are less than 4% for
iron secondaries and even smaller for boron where partial cross sections are
nearly independent of energy.

5 CONCLUSION.

We have compared the observed B/C+O and (Sc to Cr)/Fe ratio between 100 MeV/n
and 15 GeV/n to those calculated with the simple leaky box model. This calcu-
lation incorporates several important cross sections recently measured with
high accuracy [6]. The large energy range considered here allows a detailed
study of their energy dependence. At high energies our adopted rigidity
dependence agrees well with previous studies [3-9].
For the B/C+O ratio the data from 2 GeV/n down to 100 MeV/n can be accounted for
with a constant escape length if the modulation is moderately strong(350MV).
If the modulation is as strong as 500MV a turn over may be present around
2.GeV/n and a constant residence time consistent with diffusion convection
theory would agree better with the data [12].
The (Sc to Cr)/Fe ratio is less sensitive than the B/C+O ratio to the precise
shape of the escape length energy dependence below 2Gev/n. The IMP data at low
energy and the HEAO data below 2Gev/n can be accounted for with similar values
of the escape length within uncertainties,whereas at intermediate energies
larger values would provide a better agreement with the ballon data.
However, our calculations fails to reproduce the observed ratios with the same
escape length for boron and iron secondaries. This effect is quite marked at
low energies and it is still present in the HEAO data at least up to 4GeV/n.
Part of this discrepancy may be due to our interpolation of partial cross sec-
tions. Some truncation of pathlength may be indicated by the low and high
energy data as well [7-10].
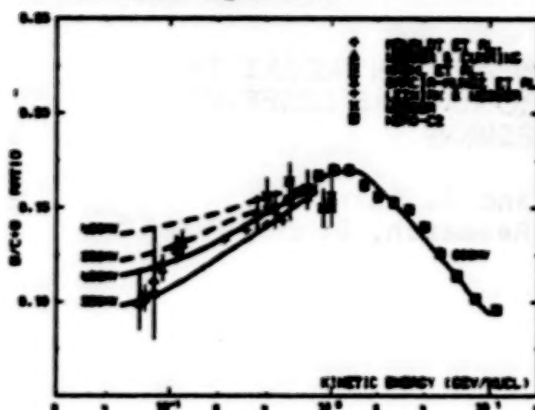
FIG 1- B/C+O RATIO
Full lines: calculated with formula
(1). See text.
Dashed lines: calculated with escape
length 7 g/cm2. Modulation level as
indicated.
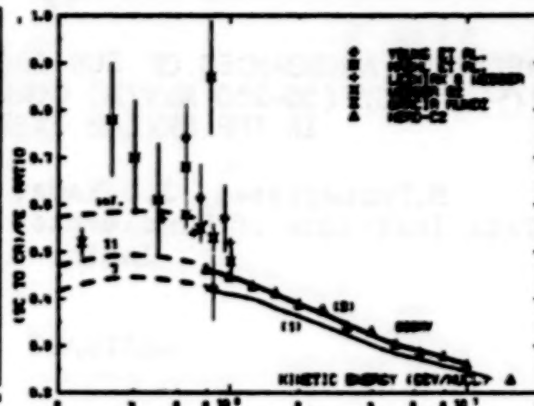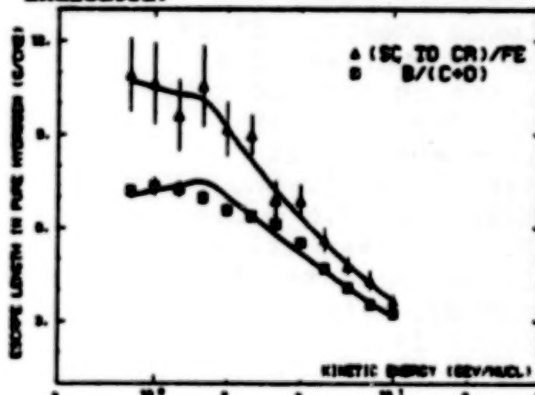
FIG 2- (Sc to Cr)/Fe RATIO
Full lines: calculated with formula
(1) or (2). See text.
Dashed lines: calculated with constant
escape length. From top to bottom:
infinite (complete confinement),
λ_{esc}=11 g/cm2 , λ_{esc}=7 g/cm2

FIG 3- ESCAPE LENGTH IN PURE HYDROGEN
FROM THE HEAO DATA.
Data points: escape length values from
observed ratio of fig 1 and fig 2.
Uncertainties: statistical only.
Full lines: calculated from formula(1)
(bottom) and formula(2) (top).

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RELATIVE ABUNDANCES OF SUB-IRON TO IRON NUCLEI IN LOW ENERGY (50-250 MeV/N) COSMIC RAYS AS OBSERVED IN THE SKYLAB EXPERIMENT

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ABSTRACT

A Lexan polycarbonate detector exposed on the
exterior of Skylab-3 for 73 days during a solar
quiet period was used to study the relative
abundances of calcium to nickel ions in low
energy cosmic rays of 50-250 MeV/N. The method
of charge identification is based on the measure-
ment of conelength (L) and residual range (R) of
these particles in various Lexan sheets. Since
more than one cone (sometimes as many as five)
is observed and is measured, the charge accuracy
becomes precise and accurate. The ratio of
(calcium to manganese) to (iron and cobalt)
obtained at three energy intervals of 50-80,
80-150, 150-250 and 50-250 MeV/N are 7.6 ± 3.8,
2.7 ± 0.8, 1.4 ± 0.6 and 3.3 ± 0.7 respectively.
These data thus indicate a large increase of
this ratio with decreasing energy. The origin
of this strong energy dependence is not under-
stood at present.

1. Introduction. The origin and propagation of low energy
(<200 MeV/N) cosmic ray nuclei in source regions, inter-
stellar space and interplanetary space could be inferred
from a study of the composition and energy spectra of
calcium to nickel nuclei of the same energy. For this
purpose, it is assumed that iron is the most abundant
element in this group in the source region. It is further
assumed that most of the other elements (calcium to
manganese) result from the spallation of iron nuclei in
the interstellar medium. The balloon studies relate to
particles of energy above 200 MeV/N. The intensity of
calcium to iron ions in the vicinity of the earth are
quite low, so that fairly large detector areas with long
exposure times outside the earth's atmosphere are
necessary to study the nuclei in the cosmic radiation.
In the present work, we report the results of fluences
and relative abundances of calcium to nickel ions in the
energy range 50-250 MeV/N. The detector used is a plastic
Lexan polycarbonate detector of collecting power
$1.1 \times 10^9 cm^2$-sec exposed for 73 days during a solar quiet
time, from 22nd Nov.1973 1800 UT to 2nd Feb.1974 1800 UT.

No prominent solar activity was recorded during this
period. Thus low energy galactic cosmic ray nuclei could
be easily observed at the Skylab orbit. The method and
accuracy of charge identification used, the estimation of
energy, fluences and relative abundances were described
earlier (Biswas and Durgaprasad 1980). A discussion of the
results will be made in the third section. Earlier results
of the work were reported before (Biswas et al.,1975,
Durgaprasad et al.,1979 and Ramadurai et al.,1984).

2. Experimental Procedure. A stack of 32 sheets of Lexan
polycarbonate sheets, each of dimensions 20 x 8.8 x 0.025
cm, covered with aluminium foil of various thicknesses
ranging from 27 mg cm^{-2} to 108 mg cm^{-2} was used to record
nuclei from calcium to iron. Actual dimensions of sheets
used in this analysis, is one-fourth sheet, each of
dimensions 10 x4.4 x 0.025 cm. The top ten and bottom ten
sheets of 32 plates were scanned for double cones and
followed further till they were either brought to rest or
left the stack. An area of about 25.0 cm^2 was scanned in
each of the top ten sheets. The trajectories of the
tracks were followed through the stack, until the end of
their ranges. Tracks due to heavy nuclei entering through
the top surface and stopping in the first ten sheets were
used for analysis of particles of energy around 60 MeV/N,
while those stopping in the bottom ten sheets were used
for analysis of particles around 150 MeV/N. The
measurement and analysis of track parameters were done
according to standard procedures (see for details Biswas
and Durgaprasad, 1980).

The charge calibration of nuclei was done as follows:
For each nucleus, track conelength (L) vs residual range(R)
plots were made. In such a plot, well defined groups of
tracks occurring for tracks of R < 100μ were assigned to
oxygen. The highest range points were ascribed to iron
nuclei. Calcium to iron nuclei in passing through the
stack give rise to various cones before coming to rest.
Charge assignment for each cone has been made to the
nearest charge ΔZ = 0.1. A nucleus may produce more
than one cone. In such a case, the most probable value
is estimated to the nearest value of 0.1 charge accuracy
($\Delta Z/\sqrt{n}$ where n is the number of cones).

Charge values have been assigned to all the cones
and later to the incident nuclei. From the residual range
and charge value, the energies have been assigned using
the range-energy relationship of Henke and Benton (1967).

3. Results and Discussion.
In Table 1, we show the fluences of particles of charges ranging from 20 to 27 for energy intervals of 50-80, 80-150, 150-250 and 50-250 MeV/N.

Table 1 - Relative Abundances(R, A) of Ca-Co Nuclei in Skylab Experiment

Z \ E	50-80 MeV/N N	50-80 MeV/N R.A.	80-150 MeV/N N	80-150 MeV/N R.A.	150-250 MeV/N N	150-250 MeV/N R.A.	50-250 MeV/N N	50-250 MeV/N R.A.
20	6	1.52	3	0.37	2	0.81	11	0.67
21	1	0.25	3	0.39	0	0.00	4	0.26
22	7	1.76	8	0.97	0	0.00	15	0.91
23	5	1.27	3	0.36	1	0.33	9	0.54
24	9	2.30	7	0.77	0	0.00	16	0.90
20-24	28	7.11	24	2.86	3	1.15	55	3.29
25	2	0.48	3	0.34	1	0.21	6	0.33
20-25	30	7.59	27	3.20	4	1.35	61	3.61
26	4	1.00	10	1.00	5	1.00	19	1.00
27	0	0.00	2	0.19	0	0.00	2	0.10
26-27	4	1.00	12	1.19	5	1.00	21	1.10
25-27	6	1.48	15	1.53	6	1.21	27	1.43

Ratio

	50-80	80-150	150-250	50-250
$\frac{20-24}{25-27}$	4.8 ± 2.2	1.9 ± 0.6	1.0 ± 0.7	2.30 ± 0.5
$\frac{20-25}{26-27}$	7.6 ± 3.8	2.7 ± 0.8	1.4 ± 0.6	3.3 ± 0.7

The relative abundances of the particles of charges of Z = 20-24 and Z = 20-25 as well as of Z = 25-27 are shown in this table. It can be seen from this table that nuclei of even charge Z = 20, 22, 24 are as abundant, if not more than, as iron nuclei in the low energy 50-80 MeV/N range. Their abundances decrease with increasing energy. The ratios of Z = 20-25/26-27 in the energy intervals of 50-80, 80-150, 150-250 and 50-250 MeV/N are 7.6 ± 3.8, 2.7 ± 0.8, 1.4 ± 0.6 and 3.3 ± 0.7.

In Fig. 1, we plot the ratio Ca-Mn/Fe obtained in balloon
and other experiments. This ratio also shows a decreasing
trend towards increasing energy. This is interpreted as that the matter traversed by the Fe group nuclei is much larger, may be as nearly as five times (Ramadurai, et al.,1984) than the ones by the high energy particles.
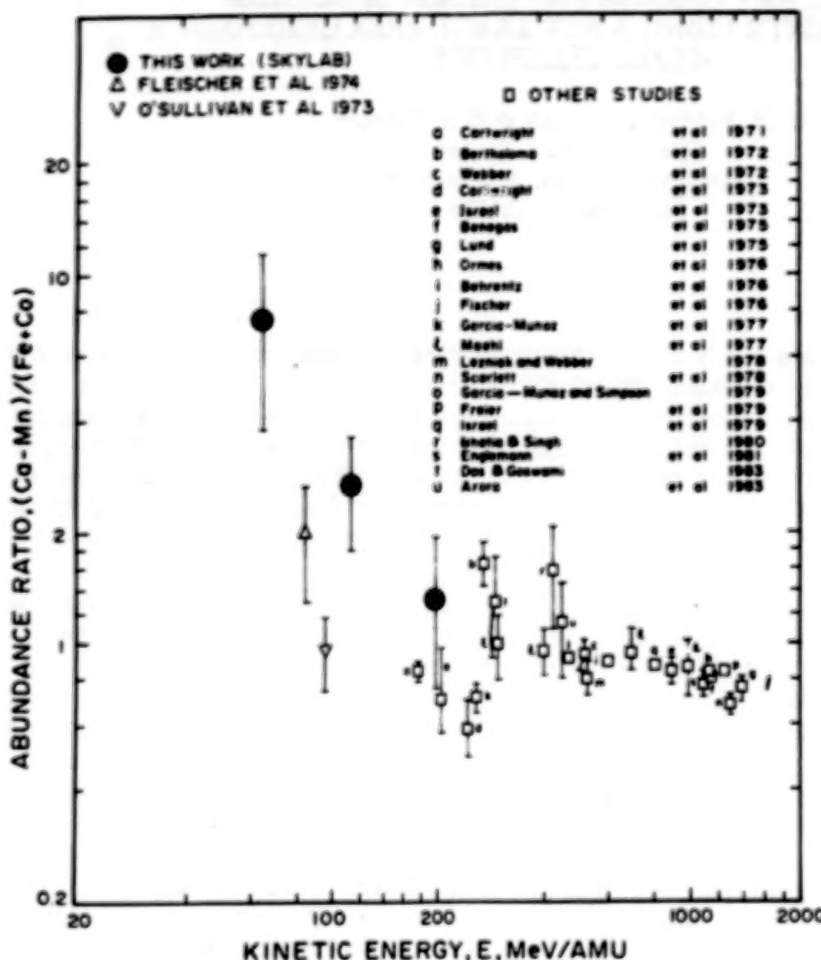
Fig. 1   Ratio of abundances of (Ca-Mn) to (Fe+Ca)
           group as a function of energy.

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COSMIC RAY CHARGE AND ENERGY SPECTRUM
MEASUREMENTS USING A NEW LARGE AREA CERENKOV x
dE/dx TELESCOPE

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1. Introduction. A detailed study of the energy spectra and relative abundance of Z = 4 - 14 nuclei contains valuable information relating to the acceleration and propagation of cosmic rays in the galaxy. Nuclei such as C, O, Ne, Mg and Si are mainly source nuclei and possible differences in their spectra at both high and low energies are sensitive measures of cosmic ray source spectra and propagation effects. Nuclei such as Be, B and N are mainly produced by interstellar fragmentation and their relative abundances provide a direct measure of the interstellar path length as a function of energy.

The most precise and complete study of the relative abundances of these nuclei is from the French-Danish experiment on board HEAO-3. This experiment, which flew in 1979-80, measured nuclei with Z = 4 - 30, over the energy range ~ 1 - 15 GeV/nuc. Engelmann et al., 1983. Absolute intensities were not reported in this experiment and a possible energy dependent bias in the flash tube efficiency for lower Z nuclei could affect the B/C ratio.

We have flown in September, 1981, a new $0.5m^2$ ster cosmic ray telescope to study the charge composition and energy spectrum of cosmic ray nuclei between 0.3 and 4 GeV/nuc. A high resolution Cerenkov counter, and three dE/dx measuring scintillation counters, including two position scintillators were contained in the telescope used for the charge and energy spectrum measurements. The analysis procedures did not require any large charge or energy dependent corrections, and absolute fluxes could be obtained to an accuracy ~ 5%. The spectral measurements made in 1981, at a time of extreme solar modulation, could be compared with measurements with a similar telescope made by our group in 1977, at a time of minimum modulation and can be used to derive absolute intensity values for the HEAO measurements made in 1979-80. Using both data sets precise energy spectra and abundance ratios can be derived over the entire energy range from 0.3 to greater than 15 GeV/nuc.

1. Instrumentation & Data Analysis. The telescope used in these studies is shown in Figure 1a. The registration of an event is accomplished by a coincidence between PS1 & PS2, defining a geometry factor of 0.46 ± 0.01 m^2-ster. The total live time is 95,800 sec. including a measured data analysis and transmission efficiency of 0.93 ± 0.01, giving an A Ω t of 44,050m^2-ster-sec. To obtain absolute intensities at the instrument the observed events need only be divided by A Ω t. All events are initially accepted for analysis, however consistency criteria are placed on the relative outputs of the three separate dE/dx counters to remove nuclear interactions etc. in the telescope. Matrices of C1 vs. the avg. of the three S counters, subject to these criteria, exhibit clearly defined charge lines as shown in Figure 1b and these matrices are directly used to obtain the various charge abundances. The major source of charge dependent uncertainty in the absolute abundances, and in the ratios we derive, comes from the

above consistency criterion correction which varies from 1.217 for B to 1.086 for S. Finally to correct the intensities to the top of the atmosphere one must consider the 7.1 g/cm^2 of material in the telescope and gondola and the 3.6 g/cm^2 of residual atmosphere. This correction amounts to a factor of 1.596 for Oxygen nuclei with an uncertainty of ± 5%. This correction ranges from 1.332 for B to 1.667 for S, and the relative uncertainty in the ratios of this correction is less than 3%.

For each charge we have constructed a histogram of events in the C dimension from the matrices as illustrated in Figure 1b. Histograms for Be through O nuclei are shown in Figure 2. This distribution of events vs. C/C_{max} may be transformed into an energy spectrum using deconvolution procedures similar to those discussed by Lezniak, 1975. In this approach there are several key steps. First the $\beta = 1$ point must be determined for each charge to an accuracy of < 1%. Second the resolution function for $\beta = 1$ particles for each charge must be determined and finally an appropriate Cerenkov relation modified for residual scintillation and knock-on electrons must be used to transform from Cerenkov output to energy. Space does not permit these procedures to be discussed in detail, however there are many tests that can be used to verify their accuracy. When one is comparing ratios of adjacent charges, for example, it is useful to form ratios of events vs. C/C_{max} such as shown in Figure 3 for B/C. The instrumental effects that could change this ratio are easily identified (e.g. the increase above $C/C_{max} = 1.0$ is caused by the different resolution for B and C nuclei) and most of the change that is observed is believed to be due to a real change in the B/C ratio with energy.

3. **Data and Discussion.** In Figure 4 we show the B/C ratio derived from this measurement and that observed by Engelmann et al., 1983. In general, there is quite good agreement, but below ~ 3 GeV/nuc our values of this ratio are lower by ~ 5-10%. Some of this difference may be due to the larger solar modulation at the time of our measurement but we believe there is also a significant difference in the two results in this energy range. Since this ratio is used by most workers to derive the amount of interstellar material traversed as well as its energy dependence, this result will lead to modifications of these conclusions. In Figure 5 we show that N/O ratio derived from this measurement and that reported by Engelmann et al., 1983. Here the agreement is excellent. We are not aware of any charge or energy dependent effects in our analysis that could produce differences of > 1-2% in our relative B/C and N/O ratios and this N/O measurement therefore seems to support the suggestion of a systematic effect in the B/C ratio.

In Figure 6 we show the Oxygen spectrum derived from this work as well as the spectrum previously reported from a 1977 balloon flight with a similar type of instrument (Webber et al., 1979). The earlier reported spectra have been modified slightly as a result of using improved data analysis procedures compatible with the analysis of the 1981 balloon flight data. It is seen that the intensity in 1981 is a factor ~ 2 lower at 1 GeV/nuc than in 1977. This is compatible with the Mt. Washington neutron monitor rates on the dates of the two measurements, which were 2365 in 1977 and 2118 in 1981 for a decrease of 10.5%. At the time of the HEAO measurement in 1979-80 we obtain an average neutron monitor rate = 2190, and the HEAO spectrum, normalized accordingly, is shown in Figure 6. This spectrum is ~ 30% lower than that utilized by Engelmann et al., 1984 where they normalized to intensity measurements made at 10 GeV/nuc. However with this new normalization, which essentially fits data between ~ 0.7 and 4.0 GeV/nuc, the HEAO intensities above ~ 10 GeV/nuc are now ~ 30% lower than the average reported intensities from several observers. This suggests possible systematic differences between the high and low energy spectra ~ 30%, which could distort the spectral shape of the derived interstellar energy spectrum in this energy range.

In Table I we present integral intensities of various nuclei > 400 MeV/nuc and 4 GeV/nuc obtained in 1981, that may be used to compare with earlier values reported in the literature.

4. **Acknowledgements.** This work was supported by a NASA Grant #NGR-30-002-052.

5. **References.**

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6. **Figure Captions.**

Figure 1a, b. Outline drawing of telescope and matrix of C, N, O events.

Figure 2. Cerenkov distributions for Be-O nuclei. Estimated resolution for $\beta = 1$ particles is shown.

Figure 3. Ratio of B/C events as a function of C/C_{max}.

Figure 4. Observed B/C ratio at top of atmosphere in 1981. HEAO data from Engelmann et al., 1983 also shown.

Figure 5. Observed N/O ratio + HEAO data.

Figure 6. Observed Oxygen spectra in 1977 and 1981 ($xE^{2.5}$) along with normalized HEAO spectrum.
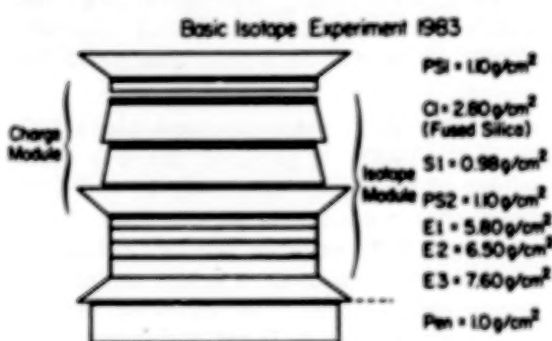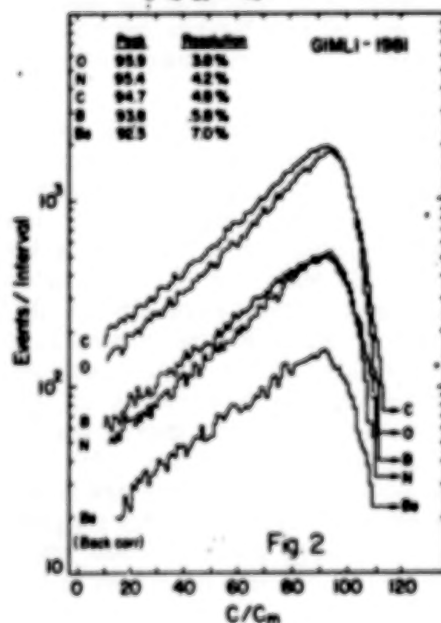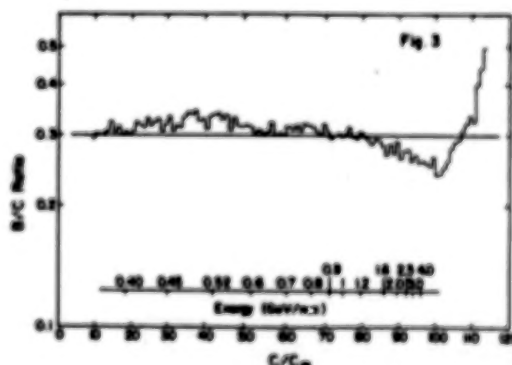
Basic Isotope Experiment 1983

PS1 = 1.0 g/cm²
O1 = 2.80 g/cm² (Fused Silica)
S1 = 0.98 g/cm²
PS2 = 1.0 g/cm²
E1 = 5.80 g/cm²
E2 = 6.50 g/cm²
E3 = 7.60 g/cm²
Pen = 1.0 g/cm²

Fig. 1a

Fig. 1b

Fig. 2

Fig. 3

Fig 5

Fig 6

Fig. 4
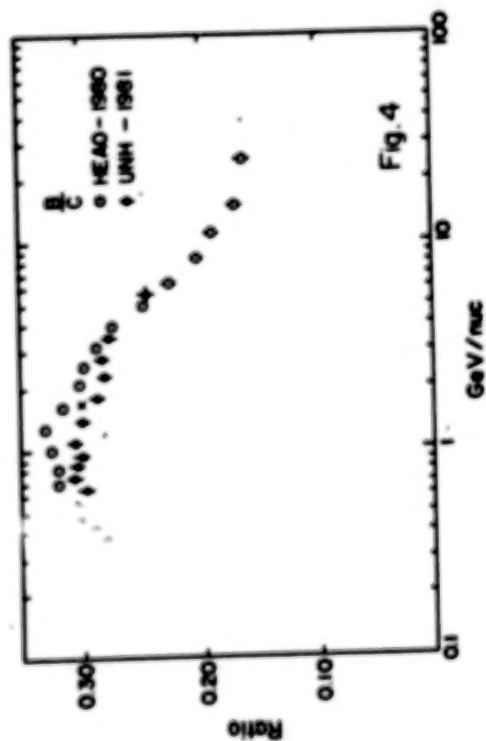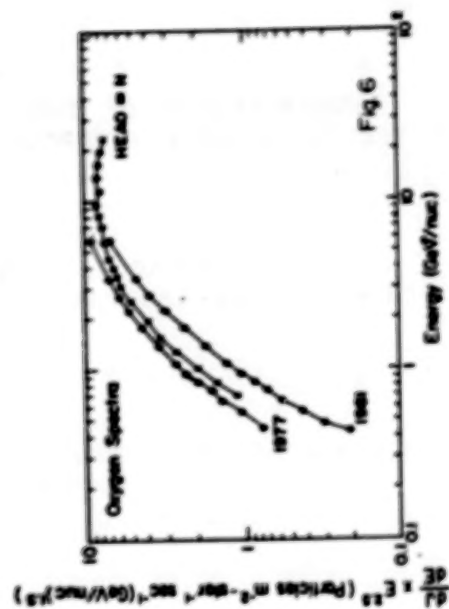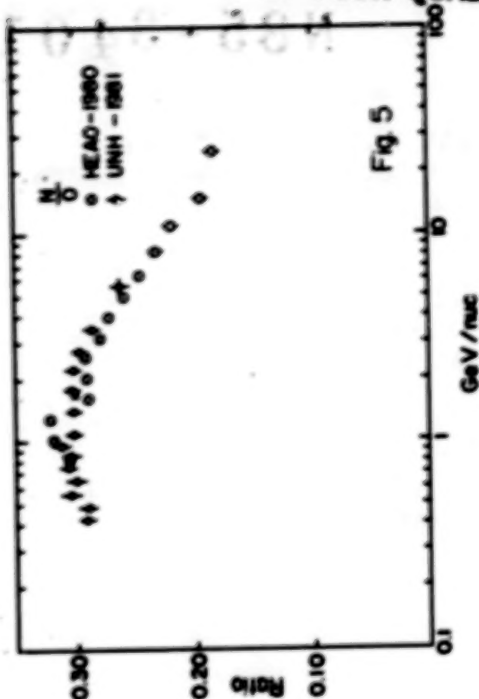
Table 1

Absolute Intensities
At Top of Atmosphere
Aug. 27-28, 1981
Balloon Flight

	> 400 MeV/nuc	> 4.0 GeV/nuc
Be	92586.[a] ± 0.3142[b]	2.295c ± 0.07640
B	28,624c ± 0.9379	7,140c ± 0.2150
C	100,860c ± 3.289	28,020c ± 0.8760
N	28,525c ± 2.959	6,960c ± 0.2240
O	89,184c ± 3.0	28,105c ± 0.8490
Ne	14,436c ± 0.48c	4,241c ± 0.1430
Mg	17,604c ± 0.6329	5,304c ± 0.1860
Si	13,056c ± 0.4879	3,476c ± 0.1440
S	2,432c ± 0.1090	662c ± 0.0327b

a   Number of events observed after selection criteria
b   Intensity at top of atmosphere in particles/m²
ster-sec. ± peters

N85-34012

A MEASUREMENT OF THE COSMIC RAY ELEMENTS C TO Fe
IN THE TWO ENERGY INTERVALS 0.5-2.0 GeV/n AND 20-60 GeV/n

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Introduction. The study of the cosmic ray abundances beyond
20 GeV/n provides additional information on the propagation
and containment of the cosmic rays in the galaxy. Since the
average amount of interstellar material traversed by cosmic
rays decreases as its energy increases, the source com-
position undergoes less distortion in this higher energy
region. However, data over a wide energy range is necessary
to study propagation parameters. We present some measure-
ments of some of the primary cosmic ray abundance ratios at
both low (near 2 GeV/n) and high (above 20 GeV/n) energy and
compare them to the predictions of the leaky box model. In
particular, the integrated values (above 23.7 GeV/n) for the
more abundant cosmic ray elements in the interval C through
Fe and the differential flux for carbon, oxygen, and the
Ne,Mg,Si group will be presented. Limited statistics have
prevented the inclusion of the odd Z elements.

Instrument and the Exposure. The instrument has been
previously described [1] and will be briefly reviewed here
with the exposure parameters. The apparatus consists of a
freon -12 gas Cerenkov detector (index of refraction =
1.001) for differential energy measurements between 20 and
60 GeV/n. Two banks of six 5-inch photomultiplier tubes
viewed the freon gas which was contained in a thin
fiberglass tank lined with millipore paper. The pulse
height information from each set of tubes allowed correction
for those cosmic ray events where a particle passage or
delta rays obviously affected one bank of tubes. Two solid
Cerenkov radiators (teflon and lucite) were included for
charge identification. The teflon (effective index = 1.36)
and pilot 425 (effective index = 1.52) radiators were placed
in individual white boxes coated with $BaSO_4$ paint and each
was observed by eight 5-inch photomultiplier tubes.

To further aid in event selection, two dual gap ion chambers filled with Xenon and a plastic scintillator (NE 102) were included. The scintillator was also housed in a light collecting box viewed by four tubes. An eight plane multi-wire hodoscope was used to determine the particle trajectory through the instrument. The track information was used in correcting the pulse height information for path length variations and for nonuniform response in the detectors, and it was an effective tool in removing background events such as showers, fragmentation events, and events outside the defined geometry of the experiment. For the detector arrangement, refer to Figure 2 in reference [1]. This instrument was flown from Pierre, South Dakota in September of 1978 at an average depth in the atmosphere of 3.6 g/cm^2. The collection factor for the flight was 2.8 M^2 ster.hrs.

Corrections to the Data. The track fitting routines screened the majority of atmospheric showers, some interacting events, and events that missed one or more of the detectors. The detector signals were corrected for the path length difference and the nonuniformity in detector response. Pulse height consistency criteria were then applied to eliminate remaining background events, mainly those interacting in the instrument. The energy calibration of the freon-12 Cerenkov counter was accomplished by isolating the elements and finding saturation values ($\beta = 1$). For oxygen, close to 150 photoelectrons were collected. Eight percent of this saturation signal was a scintillation component due to various effects including energetic delta rays. With this information, the energy measurement was unfolded following the method found in the appendix of reference [2]. The charge of the events above 20 GeV/n was determined by summing the saturated signals of the lucite and teflon Cerenkov detectors. The charge resolution (σ) obtained for events with kinetic energy >25 GeV/n was slightly better than 0.25. The separation into charge groups was done as suggested in both references [2] and [3]. The even integer charge is defined as $Z_{even} \pm 0.625$, and the odd integer charge is $Z_{odd} \pm 0.375$. The charge deconvolution or overlap corrections for C, N, and O are respectively 0.98, 1.09, 0.99 for energies greater than 25 GeV/n.

Finally nuclear fragmentation corrections for both the instrument and overlying atmosphere were performed according to the method outlined in reference [4] with the fragmentation cross-sections taken from reference [5]. The cross-sections were evaluated in the asymtotic region (E = 2 GeV/n) and applied to the 25 to 60 GeV/n energy interval with the assumption that the scaling correction is minor.

Results and Conclusions The results of the 1978 flight are listed in Tables I and II. The errors quoted are based on counting statistics only.

Table I

(E$_K$ > 23.7 GeV Per nucleon)

Integrated Flux

	in particles/(M^2·Ster·Secs)	Ratios*
C	$(5.2 \pm 0.3) \times 10^{-2}$	0.98 ± 0.08
N	$(1.2 \pm 0.1) \times 10^{-2}$	0.23 ± 0.02
O	$(5.3 \pm 0.3) \times 10^{-2}$	1.00 ± 0.08
Ne	$(1.1 \pm 0.1) \times 10^{-2}$	0.21 ± 0.02
Mg	$(1.2 \pm 0.1) \times 10^{-2}$	0.23 ± 0.02
Si	$(8.8 \pm 1.3) \times 10^{-3}$	0.17 ± 0.03
MnFeCo	$(5.9 \pm 1.1) \times 10^{-3}$	0.11 ± 0.02

* Normalized to Oxygen

Table II
Differential Flux

in particles/(M^2·Ster·Secs·GeV per nucleon)

$(N \pm \Delta N)^{-m} \equiv (N \pm \Delta N) \times 10^{-m}$

Kinetic Energy (GeV/n)	Carbon	Oxygen	NeMgSi
25.8	$(3.6 \pm 0.3)^{-3}$	$(3.6 \pm 0.4)^{-3}$	$(2.3 \pm 0.3)^{-3}$
30.0	$(2.7 \pm 0.3)^{-3}$	$(2.3 \pm 0.3)^{-3}$	$(1.4 \pm 0.2)^{-3}$
33.9	$(1.6 \pm 0.2)^{-3}$	$(1.7 \pm 0.3)^{-3}$	$(8.3 \pm 1.9)^{-4}$
39.8	$(7.2 \pm 1.1)^{-4}$	$(9.3 \pm 1.3)^{-4}$	$(4.4 \pm 1.0)^{-4}$
50.6	$(1.9 \pm 0.4)^{-4}$	$(2.3 \pm 0.5)^{-4}$	$(1.6 \pm 0.5)^{-4}$
61.8	$(4.6 \pm 0.8)^{-4}$	$(3.7 \pm 0.8)^{-4}$	$(2.5 \pm 0.7)^{-4}$

The data is in general agreement with previous balloon results. A comparison of the ratios in Table I with the French-Danish experiment on HEAO-3 [6] is within one to two sigma of their values at 25 GeV/n except for the ratio Ne/O.

In Table III, we have selected some key primary to primary cosmic-ray abundance ratios at two widely separated energies. The lower energy values were taken from a 1976 balloon flight experiment that is fully described in reference [7].

Table III

	'76' Experiment E$_k$ = 1.2 GeV per nucleon	This Experiment E$_k$ > 23.7 GeV per nucleon
O/C	0.91 ± 0.02*	1.02 ± 0.08
Fe/O	0.086 ± 0.006	0.111 ± 0.022
Si/Fe	2.08 ± 0.16	1.49 ± 0.35

* Statistical error only

These ratios seem consistent with the phenomenological leaky box model for cosmic-ray propagation described in reference [8]. Specifically we compared our O/C data to the theoretical prediction plotted on figure 15 of reference [8]. Taking note of the uncertainty in our data, we find good agreement with this propagation model that uses the source abundances of Shapiro, Silberberg, and Tsao [9].

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Relative Abundances of Elements $(20 \leq Z \leq 28)$ at Energies up to 70GeV/amu Using Relativistic Rise in Ion Chambers

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1. Introduction This paper reports on the results of a new balloon borne cosmic ray detector flown from Palestine, TX in Sept 1982. The exposure of 62 m^2-ster-hr is sufficient to prove the concept of using gas ionization chambers as energy measuring devices in the relativistic rise region. We have measured the abundances, relative to $_{26}Fe$, of the pure secondaries $_{22}Cr$ and $_{24}Ti$, the pure primary $_{28}Ni$, and the mixed primary and secondary $_{20}Ca$ between 6 and 70GeV/amu.

2. Instrument The instrument, shown in figure 1, is composed of 1.0cm NE114 plastic scintillator(S), and 0.6cm Pilot 425 plastic Cherenkov(P), detectors in light diffusion boxes. These two detectors determine the charge of the cosmic rays. Interspaced around the S and P detectors are pairs of 10cm dual gap P-10 gas ionization chambers(I). In addition to being the energy measuring devices they are also used for identification of nuclear interactions in S and P detectors. At the bottom of the stack is a one atmosphere CO_2 gas Cherenkov(G), whose nominal threshold energy is 34.8GeV/amu. This detector provides the energy calibration of the relativistic rise region of the ion chambers. The two layers of x-y multiwire ionization hodoscopes(H) provide the trajectory information which allows for the path length correction and for correction to the areal variations of the various detectors. The stack, 160cm x 160cm x 190cm, with the electronics is flown inside a one atmosphere pressure vessel.

Figure 1

3. Data Reduction Figure 2 is a plot of the mean ionization signal(I) versus the plastic Cherenkov signal(P). The dashed lines are the charge tracks for the even Z elements 20 to 28. The vertical pairs of lines mark the $\beta=1$ saturation of P, the events of interest in this experiment. With I and P alone it is impossible to separate, say, relativistically risen charge 24 from low energy charge 26. To remove this ambiguity a third dimension, scintillation(S), is added.
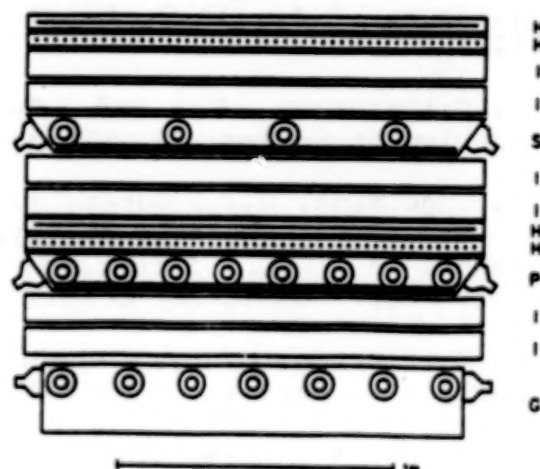
Figure 3 is a plot of the same events for S versus P. The energy dependence is almost entirely in the P dimension. The relativistic events pile up at the right side of the cluster and lower energy events trail off towards the left. The superposed boxes are the S and P cuts used to select events that will be used to form abundance spectra. We observe that S has negligible (less than 0.5%) relativistic rise at 100GeV/amu, so the S cuts do not introduce a significant energy dependence.

Figure 2

Figure 3
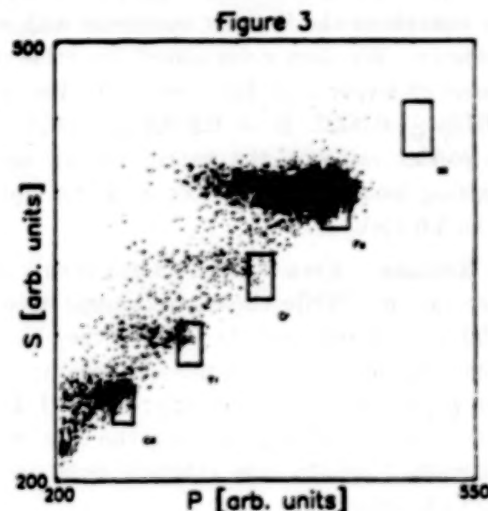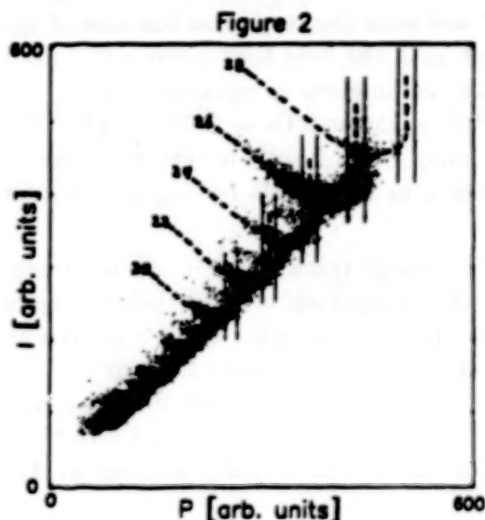
The S cuts are asymmetric about the charge tracks. This is because almost all the contamination from adjacent charges into a given charge selection box is from the lower energy next higher charge. The P cuts are symmetric about the $\beta=1$ track of the given charge. Both the S and P cuts are made in constant sigma units for each charge. This insures a constant fraction of the desired charge to be included within the S-P box cuts. Taking the events within these cuts, histograms were formed in I/I_{min}. Ratios of these histograms to that for iron are the abundance ratio spectra that are discussed in section 5.

4. Energy Calibration

Figure 4 is a plot of I vs G for the events satisfying the S and P cuts in figure 3 for iron. The line through the data is a result of a least-squares fitting with the semi-empirical model described by equations 1.

$$I = I_m \ln(E) + B \qquad (1a)$$

$$G = K(1 - E_{thresh}^2/E^2) + D \qquad (1b)$$

I is the ratio of the I signal over the minimum value (at 2.4GeV/amu). The D term represents the scintillation emission from the reflective paint coating on the inside of the G light diffusion box.

The fitting was done in two steps. The first attempt only fit the events between the G values of 450 and 1100. Using this fit a swath through I and G

Figure 4
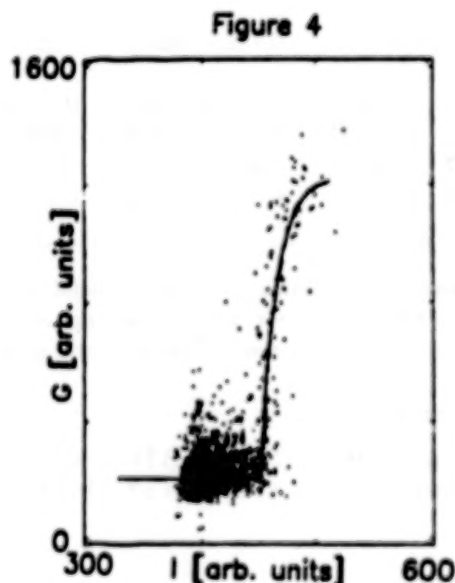
space was made to allow for the inclusion of events down beside the paint emission clump and to extend the high end to include the $\beta=1$ events in the G detector. The sharp threshold in G can be seen and it is the I value at this E_{thresh} that provides one well defined calibration point. Given the limited number of events the slope (Im) was very poorly determined from this I vs G comparison, and so we instead determined the slope by comparison between our iron data and the iron spectrum from previous experiments (summarized by Webber[1]).

For various values of Im, with B selected to give the previously determined $I(E_{thresh})$, we convolved the Webber spectrum with equation 1 and with the resolution function of the detector. We then determined the value of Im which gave the best least-squares fit to our observed I-spectrum for iron. The final values of the parameters in equation 1 are $I_m = 0.0738 \pm 0.0023$, $B = 0.8889 \pm 0.0019$, $K = 1220.0 \pm 15$, and $D = 207.0 \pm 4.0$. The numerical values of the parameters for equation 1a apply to an I scale in which minimum-ionizing iron gives $I=1.000$, and this equation is taken as applicable for energies greater than 5.0 GeV/amu.

5. Results Even with the tight S cuts near the Z+1 charge track, there is still some contamination. While these contamination events are of low intrinsic energy, their I mimics relativisticly risen events because they have a greater charge. The upper S cut was fixed by requiring that the contamination to any of the five charges never be more than 20% of the charge of interest at the appropriate I/I_{min} value. Subtractions were made for these contaminations. After producing the number versus I/I_{min} spectra, they are binned into three differential points, one integral point, and using similar S and P cuts, a point at I_{min} (2.4GeV/amu).

Our results are listed in table 1 and plotted (points with error bars) in figure 5. In the energy interval 6 to 25 GeV/amu our results are consistent with those of Englemann[2] (their data has been propagated through 4.1 g/cm² of air). Above 25 GeV/amu our results indicate an energy dependence of relative abundances which continues the trend observed by Englemann, et al.

TABLE 1 - Abundance Ratios to Iron for Ti, Cr, Ca, and Ni					
Energy Range		Element			
Lower	Upper	Ti	Cr	Ca	Ni
~1.45	~3.35	0.158 ± 0.007	0.161 ± 0.007	0.217 ± 0.009	0.055 ± 0.004
5.90	11.62	0.129 ± 0.013	0.124 ± 0.013	0.225 ± 0.018	0.052 ± 0.008
11.62	22.87	0.101 ± 0.023	0.086 ± 0.021	0.178 ± 0.032	0.037 ± 0.014
22.87	45.02	0.059 ± 0.023	0.074 ± 0.026	0.092 ± 0.029	0.034 ± 0.017
45.02	∞	0.070 ± 0.023	0.075 ± 0.024	0.126 ± 0.032	0.043 ± 0.018

References:

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[2] Englemann J.J., et al, 1983, ICRC, Bangalore, India, OG1-9, pp 17

Figure 5

Calcium

Nickel

Titanium

Chromium

ABUNDANCE RELATIVE TO IRON
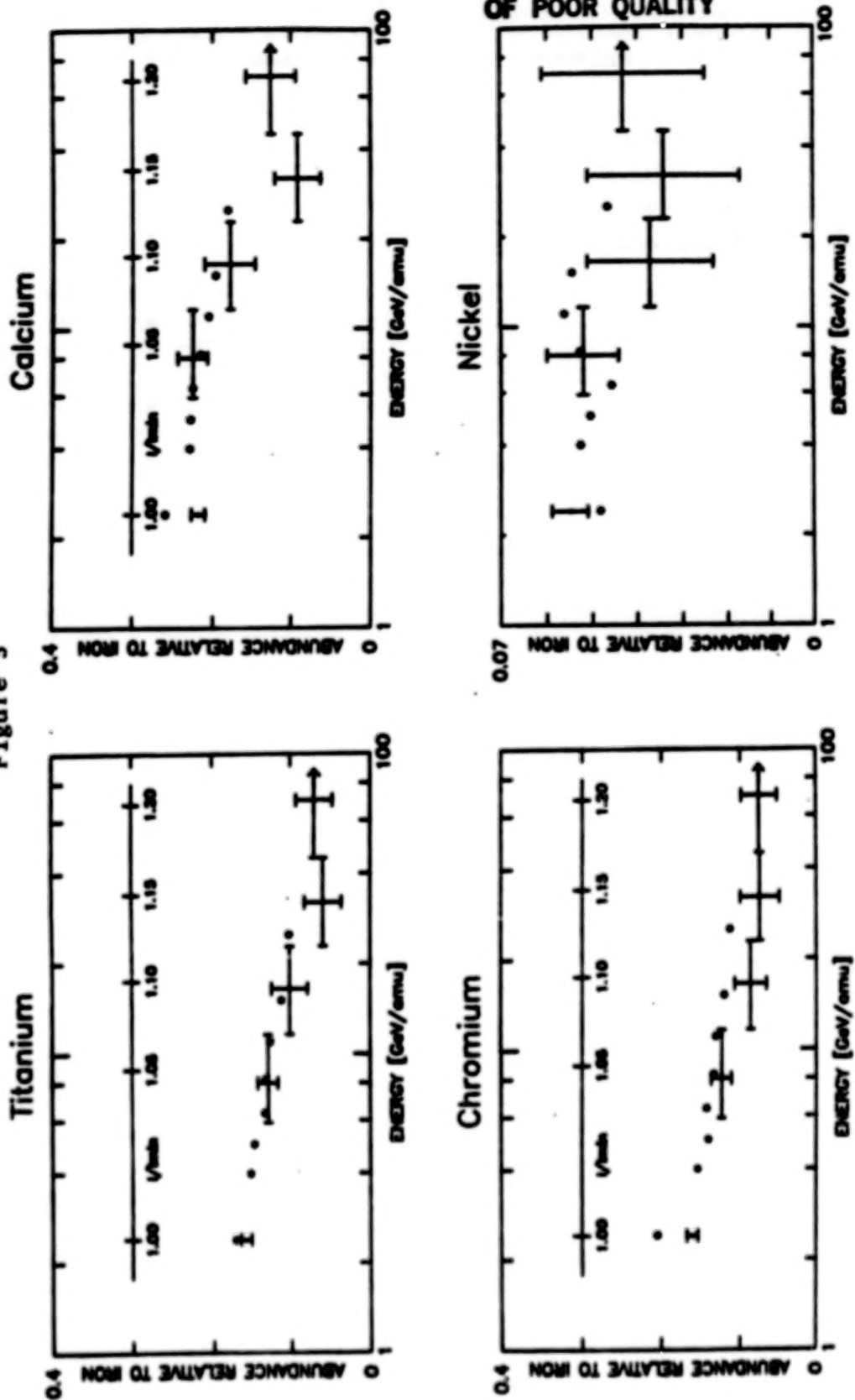
ENERGY [GeV/amu]

ENERGY SPECTRA OF ELEMENTS WITH $18 \leq Z \leq 28$
BETWEEN 10 AND 300 GeV/amu

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1. Introduction. The HEAO-3 Heavy Nuclei Experiment (Binns, *et al.*, 1981) is composed of ionization chambers above and below a plastic Cherenkov counter. We have measured the energy dependence of the abundances of elements with atomic number, Z, between 18 and 28 at very high energies where they are rare and thus need the large area x time of this experiment. We extend the measurements of the Danish-French HEAO-3 experiment (Englemann, *et al.*, 1983) to higher energies, using the relativistic rise of ionization signal as a measure of energy, and determine source abundances for Ar and Ca.

2. Data Analysis. We confine this analysis to events in the 1.1 m^2sr in which the cosmic rays penetrate all six ionization chambers, and to the first 370 days of the flight, when all six ionization chambers were functioning properly. These selections give the highest possible ionization resolution. We select only events incident with geomagnetic cutoff greater than 8 GV, so Z is determined by the Cherenkov signal. We further require agreement between the means of the three ionization chamber signals above the Cherenkov and those below, to eliminate most nuclear interactions inside the instrument.
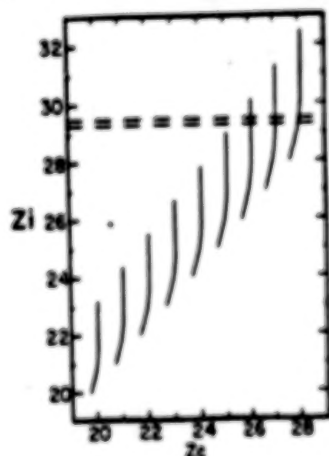
Figure 1
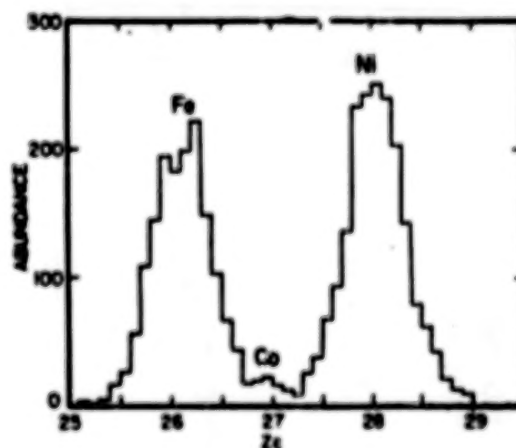
Figure 2

Figure 1 is a schematic plot showing the locus of events for each element, $20 \leq Z \leq 28$. Zc is the square-root of the Cherenkov signal normalized so $Zc \simeq Z$ at high energy. Zi is the square-root of the ionization normalized so $Zi = Z$ at minimum-ionizing. Figure 2 is a histogram of Zc for events with $29.3 < Zi < 29.5$, the region between the dashed lines in figure 1. This histogram includes Fe, Co, and Ni at about 130, 34, and 12 GeV/amu respectively. The abundance of each element in each of eighty such histograms is determined by maximum-likelihood fitting.

Corrections to these raw abundances were calculated to account for interactions both in the lid in front of the first ionization chamber and in the Cherenkov counter and other material between the ionization chambers. The latter calculation included only charge changes of one or two charge units, other interactions having been eliminated by the requirement for agreement between upper and lower ionization chambers. The calculation assumed that at all energies the total cross-sections were given by the formula of Westfall *et al.* (1979) and the partial cross-sections for changing by n charge units were the same fraction of the total cross-section for any projectile as was measured by Webber and Brautigam (1982) at 980 MeV/amu for Fe on C. These calculated corrections lowered the raw abundance ratios by typically 10 to 30 percent.

3. Energy Scale. We used Z_i/Z as a measure of energy, and derived an empirical energy calibration by comparing our Fe observations with an Fe energy spectrum derived from a compilation of previously published measurements (Webber, 1982). This Fe spectrum was multiplied by an empirical geomagnetic transmission function which represented the fraction of time when the geomagnetic cutoff permitted Fe of that energy to reach the instrument; the product was the effective Fe spectrum at the instrument, averaged over many orbits. This energy spectrum was then converted to a Z_i/Z spectrum using a trial form of the energy dependence of Z_i/Z. Finally this calculated spectrum was folded with the instrument's ionization resolution, and the resulting Z_i/Z spectrum was compared with the data. The process was iterated, by changing the assumed form of the energy dependence of Z_i/Z, until the calculated and observed spectra of Fe agreed.

The resulting energy dependence is consistent, between about 10 and 100 GeV/amu, with one derived independently for a different detector system by Barthelmy *et al.* (1985, OG 4.1-7). Above about 200 GeV/amu, the shape of our calibration curve depends upon the assumption we made that the Fe energy spectrum falls as a power-law with exponent -2.7 at energies above those where it has been measured.

Abundance ratios derived from data in a particular Z_i/Z histogram were plotted at the mean energy from which those particles came, assuming the Fe energy spectrum and the calibration curve described above. The energy resolution implied by our ionization resolution of 0.40 charge units is comparable to the spacing of the points in figure 3.

4. Results. Figure 3 gives the resulting abundances of several elements relative to Fe as a function of energy. The X symbols are the results of the DF experiment (Englemann, 1983), while the O symbols are the results of this experiment. In every case our results are consistent with those of the DF experiment in the interval where both experiments apply, 10 to 25 GeV/amu. At higher energies our data generally continue the DF trend.

Our data above 10 GeV/amu suggest a Ni/Fe ratio slightly dependent upon energy, with a best fit power law of exponent -0.050 ± 0.016. If we ignore this slight variation with energy, then the mean value of the Ni/Fe ratio over our data is 0.054 ± 0.001.

For the secondary ratios, K/Fe, Sc/Fe, Ti/Fe, and V/Fe, our data indicate an extension to about 100 GeV/amu of the same power law dependence as was indicated by the DF data. Figure 4 shows the best fit exponent for each of these ratios combining the DF and our data. The steepening of the slope with decreasing Z is expected as lower Z elements have greater contributions from tertiary nuclei.

Figure 3
Abundances relative to Fe
x Englemann, *et al.* (1983)
• This work.
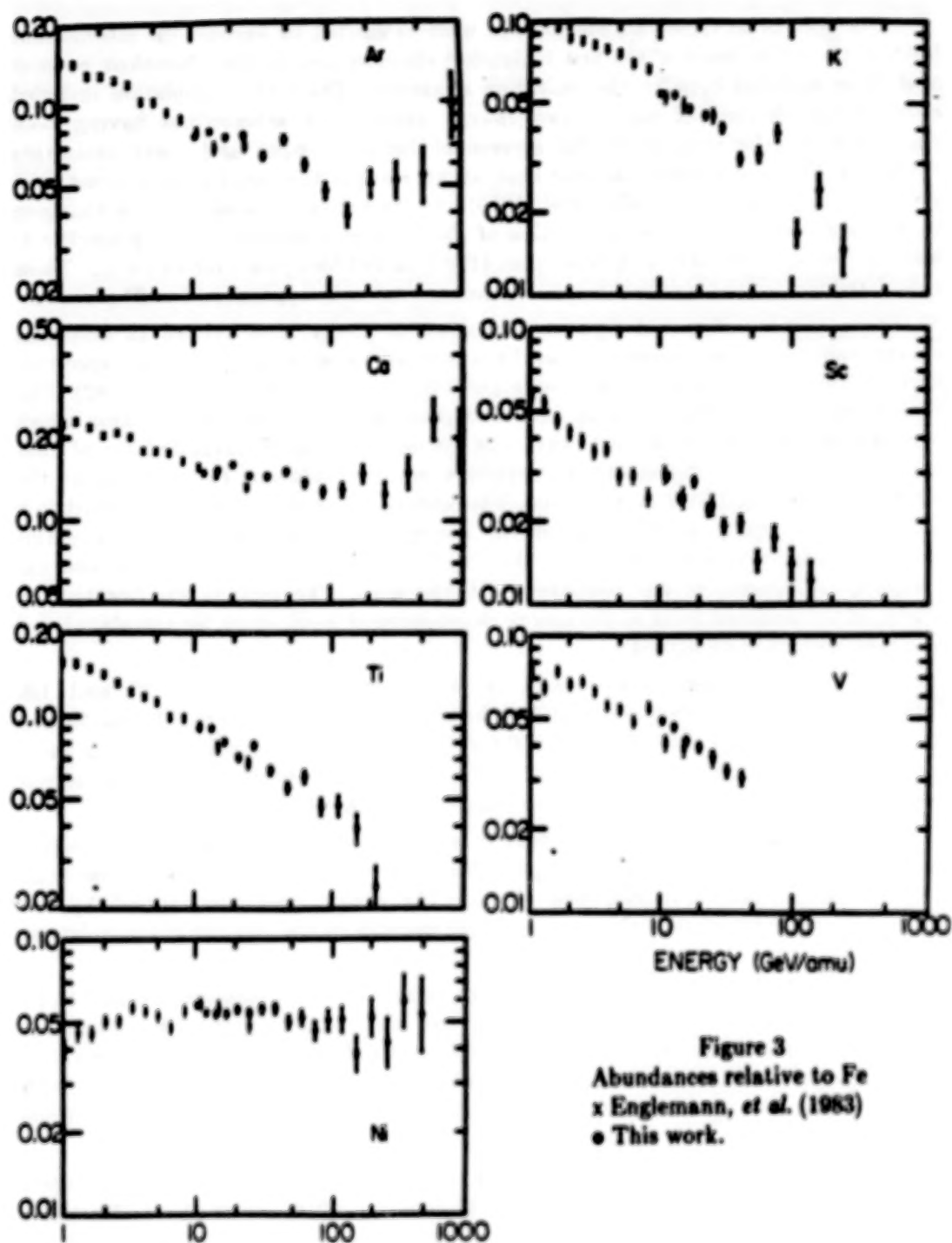
Our data indicate a leveling of the Ca/Fe ratio above the energies of the DF experiment, as would be expected from an energy-independent primary component becoming increasingly significant at higher energies as the secondary component becomes less abundant. We fitted the combination of the DF and our ratios to a function $aE^p + b$. With $p = -0.295 \pm 0.010$, interpolated from figure 4, the result is primary Ca/Fe $= 0.094 \pm 0.004$. A galactic propagation calculation on the DF data (Lund, 1984) gives a source abundance of Ca/Fe $= 0.065 \pm 0.019$.
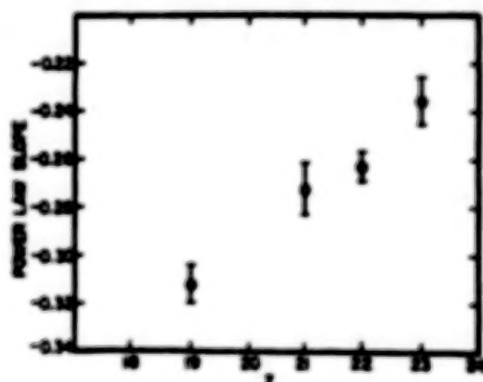
Figure 4
Exponent of power law fit to abundance of element Z relative to Fe.

A similar fit to the energy dependence of Ar/Fe, but with $p = -0.33 \pm 0.01$, gives primary Ar/Fe $= 0.026 \pm 0.003$. Propagation of the DF data (Lund, 1984) gives Ar/Fe $= 0.032 \pm 0.008$. Source abundances inferred from such galactic propagations on observed abundances 2.5 to 5 times higher must depend critically upon the adopted fragmentation cross-sections, while our extension of observations above 100 GeV/amu permits inference of source abundances without galactic propagation calculations.

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PRIMARY COSMIC RAY SPECTRA IN THE RANGE 20-60 GeV/n

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ABSTRACT

Energy spectra for primary cosmic rays C-Fe above 20 GeV/n were measured on a balloon flight from Greenville S.C. in June 1982 with a hybrid electronic counter-emulsion chamber experiment. Fluxes above the atmosphere appear in general agreement with previously published values. The heavy events included in this data will be used along with the JACEE passive chamber data to provide a heavy composition direct measurement from 10^{12} to 10^{15} eV total energy.

INTRODUCTION

The JACEE collaboration has been using emulsion chambers since 1979 in a series of balloon flights to measure the composition, energy spectra, and interactions of energetic (>1 TeV/n) cosmic rays. The apparatus used in JACEE's 0,1,2,4,5 have been largely passive, events being detected by the development of dense electromagnetic showers which produced visible dark spots in x-ray films. In 1982 a different kind of experiment was flown by the collaboration. This incorporated electronic detectors mounted above an emulsion chamber. The counters were used to define the charge and energy of incident primaries and provide trajectory information so the primaries could be traced through the emulsion chamber from the top down. For heavy ions this has proven to be an efficient process, and the results of measurements on ~130 heavy interactions (Z>22) at primary energies >20GeV/n are described at this conference.

The primary objective of this experiment was to obtain a statistically significant sample of heavy ion interactions in the energy range 20-60 GeV/n, below the energy range of detection for totally passive chambers. Other objectives were to allow direct calibration of some techniques used in JACEE, albeit in a lower energy range than the other experiments. The electronic counters also allowed the direct measurement of heavy primary cosmic ray fluxes in the range 20-100 GeV/n (1-5 TeV total energy for Fe) for comparison with the other JACEE direct composition measurements above 10^{13} eV total energy, (see paper OG4.1-13 this conference). In this paper we describe the measurement of the abundances and spectra of elements from C to Fe above 20 GeV/n.

Experimental

The apparatus was previously described (Ref.1) and is only briefly reviewed here. It consisted of two solid Cerenkov counters (Teflon and lead-glass) which were in saturation at the energies reported here and provided primary charge definition; a gas Cerenkov counter (1 atmosphere Freon-12, 81 cm most probable depth) which provided differential energy measurement in the range Eo = 20 - 65 GeV/n; and an eight-plane multiwire proportional counter hodoscope which enabled particle trajectory intersection points in the top layers of the emulsion chamber to be found with rms position error 3.5 mm. A scintillation counter was placed below the emulsion chamber to provide a measure of shower-size from individual energetic interactions within the chamber. (paper HE1.4-1 this conference)

A cross-plot of the outputs of the Teflon (CT) and lead-glass (ClG) Cerenkov counters allowed separation of individual charge identification. The ratio CT/CLG at Eo>20GeV/n gives a narrow distribution for all particles passing through both counters without interacting. This effect was used, together with the hodoscope track information to reject most events interacting in the electronic instrument. All detector signals were corrected for path-length in the detector, PM tube temperature, detector non uniformities, and ADC offsets. Charge resolution was limited by back-scatter from the emulsion chamber, an effect which was assessed by correlation of CT and CLG signals with the burst scintillator. Charge resolution was = 0.25 charge units FWHM at oxygen and 0.5 at Fe. Figure 1 shows a charge histogram of a portion of the data. For the gas Cerenkov detector, in which the PM tube outputs were analyzed in four sets of tubes, assessment and correction for δ-ray effects in tube windows was possible. Energy assignment for individual events was made using a Monte Carlo method which incorporated the instrument response function and an assumed cosmic ray spectrum. The response function was based on normal statistics of photoelectrons from Cerenkov light plus a scintillation and $BaSO_4$ paint Cerenkov contribution. The flight oxygen gas-Cerekov data is shown in Figure 3. It should be noted that energy assignments based on this method are insensitive to changes in γ of 0.3 or so.

The balloon and instrument were launched on June 2nd from Greenville, S.C. and cut down near Roswell, N.M., after 39 hours at a mean float depth of 4.9 g cm^{-2}. Effective live time was 35.6 hrs. yielding an exposure of 5.7 m^2 sr hrs of the best quality data. The geometric aperture 0.16 m^2 sr in this case included all the electronic detectors except the burst-counter.

RESULTS

The derived differential energy spectra for the principal elements and groups are shown in Figures 3 to 6, using data at the instrument. Note that the amplitudes given in these figures are per 5 GeV bin and for the whole flight. Calculation of the differential and integral intensities at the top of the atmosphere using average values of atmosphere and instrument fragmentation show essential agreement with the HEAO C-2 data. Maximum likelihood fits have been made to the raw spectra above 25 GeV/n and derived values of γ are given in the table ($dN/dE = AE^{-\gamma}$). Although primary/secondary element ratios await the full interaction correction, an estimate of the Fe/C+O ratio above 25 GeV/n is 5.4×10^{-2}, if the ratio of the interaction corrections for Fe and (C+O) is taken as 1.12. This primary ratio has been reported as 6×10^{-2} (Refs. 2,3).

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TABLE 1

MAXIMUM LIKELIHOOD FITS TO ELEMENTAL SPECTRA ABOVE 25 GeV/n ASSUMING SIMPLE POWER LAW, $dN/dE = AE^{-\gamma}$

	A	γ
	Particles $(m^2 sr\ s\ GeV/n)^{-1}$	
Oxygen	21.7	2.77 + 0.07 (-0.04)
Neon	4.2	2.72 + 0.13 (-0.12)
Magnesium	1.5	2.44 + 0.12 (-0.10)
Silicon	5.8	2.85 + 0.15 (-0.10)
16 z 25	1.4	2.89 + 0.18 (-0.10)
Iron	0.51	2.79 + 0.25 (-0.19)
Sum of Z=8,10,12,14	5.8	2.72 + 0.05 (-0.06)

Fig. 1. Charge Histogram of Flight
Data; $E_0 \geq 20$ GeV/n

Fig. 2. Histogram of Oxygen Data
in the Gas Cerenkov
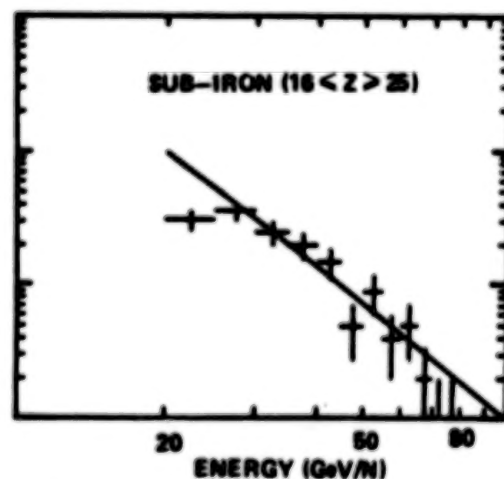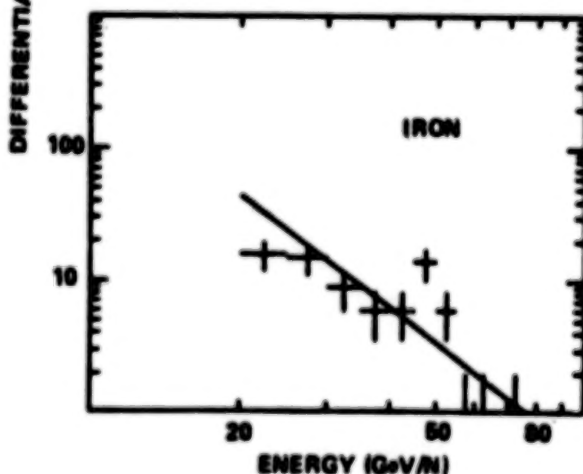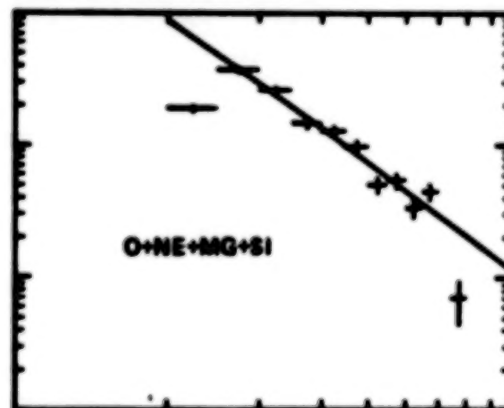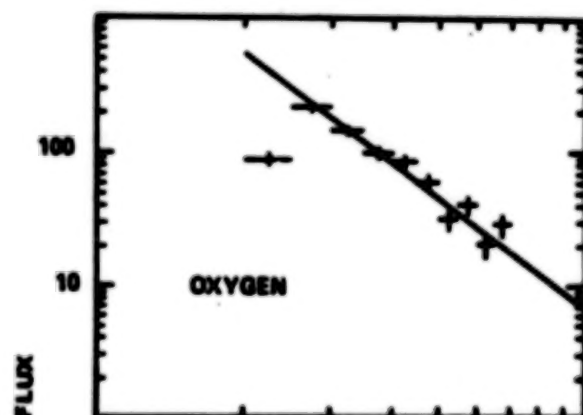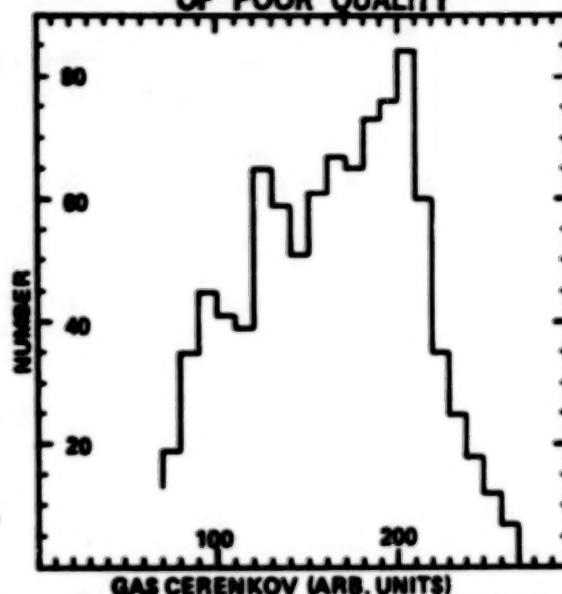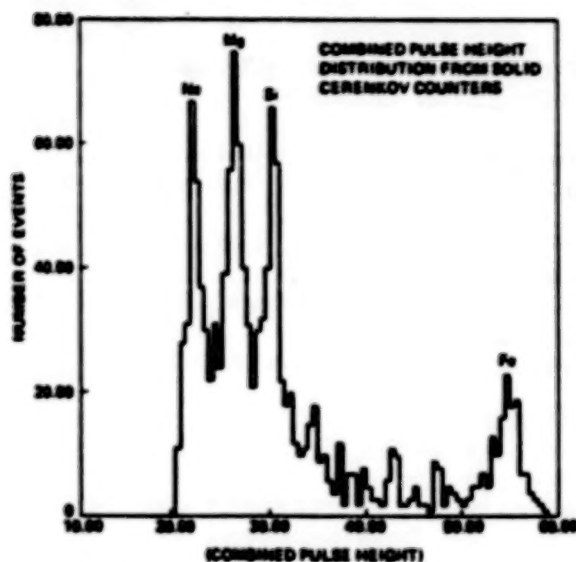
Figures 3-6. Differential Spectra of Individual Elements and Groups of
Elements Measured at the Instrument. Note that Amplitudes are per 5 GeV
bin and per Entire Flight, and Interaction Corrections have not yet been
applied. Straight Lines are M-L fits to the Data.

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ENERGY SPECTRUM OF COSMIC-RAY IRON NUCLEUS OBSERVED WITH EMULSION CHAMBER

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ABSTRACT

Energy spectrum of cosmic-ray Fe-nucleus has been measured from 4 GeV per nucleon to beyond 100 GeV per nucleon. The data were obtained using emulsion chambers on a balloon from Sanriku, Japan. The energies were estimated by the opening angle method after calibrated using 1.88 GeV per nucleon Fe collisions. The spectrum of Fe is approximately $E^{-2.5}$ in the range from 10 to 200 GeV per nucleon. This result is in good agreement with those of other experiments.

1. Introduction.

The current experimental data on the primary spectrum above 1 GeV/n are recently reviewed[1]. Concerning iron nucleus spectrum, it is interesting to establish the spectrum above 100 GeV/n. because the propagation and escape of cosmic rays from galactic confinement would make a effect on the primary spectrum above 100 GeV/n on basis of energy dependent L/M and sub-iron/iron ratio. But, the statistics of high energy data around 100 GeV/n is not sufficient for the discussion. The recent spectrum results have been obtained using instruments such as ionization spectrometers[2], gas Cerenkov counters[1,3,4]. magnetic spectrometers[5], and emulsion chambers[6,7]. There were some differences between different techniques. In this experiment, we used an emulsion chamber and applied the opening angle method for estimating the primary energy. In an emulsion chamber experiment, there were three problems to be solved: (1) The shortening of the scanning time for nucleus-nucleus collisions. (2) Charge determination of heavy nuclei. (3) Energy determination of primary nucleus, whose problem was pointed out by Kullberg et al.[8]. By developing a new detection method with plastic detector CR-39, the scanning time was shortened[9]. To reach the reliable results on 2) and 3) problem, the calibration experiments were carried out by exposing the same type of chambers as the balloon-borne one to 1.0 GeV/n and 1.88 GeV/n Fe beams at LBL heavy iron accelerator.

2. Experimental procedure

A schematic diagram of the instruments is shown in Fig.1. The emulsion chamber consists of 9 plastic track detector CR-39 plates, 27 nuclear emulsion plates and 20 polyethylen target

plates. which are piled alternately. The CR-39 plates are about 1.7 mm thick. The emulsion plate is coated with 50 μm thick nuclear emulsion gel on both sides of a 1.0 mm thick lucite plate. The target plates are 1.0 mm thick polyethylen. The overall size of 6 chambers is 1.5 m x 0.8 m x 8.9 cm and the total depth is 8.3 g/cm² . These chambers have been exposed by balloon flight at Sanriku Balloon Center, Japan, for about 15.5 hours at an altitude of 7.6 g/cm² .
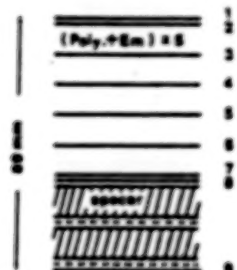
A CR-39 sheet at the top of chamber was generally scanned with a microscope of 40 magnification and the radius of located cones was measured on an adjacent downstream CR-39 plate. The charge resolution is about $\Delta Z=+/-1$.

Fig.1 Chamber design.

Selected cones of charge Z=26+/-1 were followed downstream using CR-39(No.3,5,7). Collisions were found by checking whether or not the cone became smaller or disappeared downstream. The angles of secondary particles and fragments were measured in nuclear emulsion plates.

For iron nucleus of Z=26+/-1, the integral flux is obtained using collision mean free path of λ = 15.6 g/cm² for Fe-air collision as follows:

$$I(>= 4.0 \text{ GeV/n}) = (1.2 +/- 0.1) \times 10^{-1} \quad (\text{m}^2 \cdot \text{str} \cdot \text{sec})^{-1}$$

where 4.0 GeV/n is vertical-cut-off kinetic energy at Sanriku.

3. Energy determination and correction.

We carried out an experiment using 1.88 GeV/n Fe beam at LBL to calibrate the primary energy estimated by the opening angle method. There are two methods to estimate the incident energy from the emission angle of alpha particles and heavy fragments. One is by the mean angle and the other is by root-mean-square angle. The incident kinetic energy can be calculated by the following relations:

$$P_o = \langle P_t \rangle / \langle \theta \rangle \quad , \quad P_o = \sqrt{\frac{M \langle E_k^* \rangle}{3}} / \sqrt{\langle \theta^2 \rangle}$$

where P_o is incident momentum, and $\langle P_t \rangle$ and $\langle E_k^* \rangle$ are parameters. As it is very difficult to measure the incident axis of interaction in the cosmic ray, emulsion chamber experiment, we must take the center of geometrical weight of heavy and alpha fragments in the forward cone as the axis of interaction. The parameters were calculated for the events of Nh+N$_\alpha$ >= 3, where Nh means number of heavy fragments with charge greater than 3 and N$_\alpha$ is number of alpha particles. They are shown in Table 1 for each charge range of fragment.

Zf	$\langle P_t \rangle$ (MeV/c)	$\langle E_k^* \rangle$ (MeV)
2	86.7 +/- 6.5	33.5 +/- 5.1
3 - 8	64.6 +/- 11.4	18.7 +/- 7.5
9 - 12	61.4 +/- 4.4	17.4 +/- 2.8
13 - 15	54.0 +/- 5.5	14.2 +/- 3.1
16 - 21	37.3 +/- 4.1	5.9 +/- 1.2

Table 1. Parameters for primary energy estimation. Zf means a charge of fragment.

Using these parameters. we can conversely estimate the incident energy from experimental values of $\langle\theta\rangle$ and $\langle\theta^2\rangle$. and can obtain the error distribution of estimated energy when the incident energies are known. Figure 2 shows E/E_0 distribution for 114 events with $Nh + N_d \geq 3$ obtained by the above two methods. where E means the estimated primary energy and E_0 means the beam kinetic energy of 1.88 GeV/n. The mean values of estimated energy are larger than beam energy. It is mainly due to the tail of angular distribution of alpha particles and fragments at large angles. So. if we apply the opening angle method to observe the primary energy spectrum of heavy nuclei. we must be careful of the overestimation of primary energy.

To check the effect of the estimated energy error on the primary spectrum. a Monte Carlo simulation has been made assuming the integral spectrum is a $E^{-2.5}$ spectrum at high energy. which is modulated by cut-off rigidity at Sanriku. and using the E/E_0 distribution in Fig.2. which has an approximate form of gamma function. i.e. $f(x)= x^a \cdot \exp(-bx)$ with a=3.1 and b=0.42 . It is also assumed that a form of E/E_0 distribution does not vary with primary energy E_0 . The results is shown in Fig.3 . The spectra are multiplied by $E^{2.5}$ to emphasize spectral features. It can be seen that the observed spectrum by the opening angle method is higher than the true one. Then we must correct the observed spectrum. We can also obtain a correction factor from this simulation if spectral index is known.
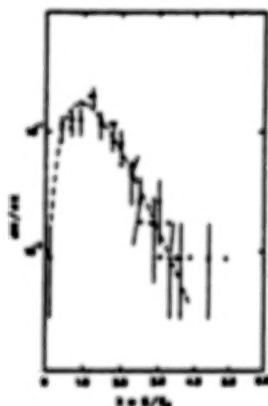
Fig.2 Estimated energy error distribution. E means the estimated primary energy and E_0 means the beam kinetic energy 1.88 GeV/n. o and A denotes the E/E_0 data obtained by mean angle and root-mean-square angle method. respectively.
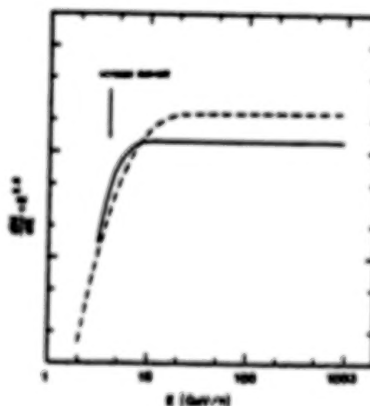
Fig.3 Results of a simulation. A differential spectrum is assumed to be $E^{-2.5}$. The broken curve is a estimated spectrum using the error distribution in Fig.2.

4. Results and discussion.

We observed 294 events of primary charge. Z=26+/-1. which make a collision in a chamber and have secondary fragments of $Nh+N_d \geq 3$. The primary energies of these events were calculated from mean emission angle and root-mean-square angle. respectively. using parameters shown in Table 1. The spectral index is consistent to -2.5 within an experimental error by comparing the experimental with a Monte Carlo simulation of spectral index of -2.3.-2.5 and -2.7 . Using this index, the

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simulation makes it possible to correct the observed spectrum. The corrected energy spectrum is shown in Fig.4 along with some data from other groups. The agreement between different measurements is quite good within the quoted errors. This experiment shows that an iron spectrum has a spectral index -2.5 in the range from 10 GeV/n to 100 GeV/n. The present data do not suggest that iron spectrum gradually becomes steep to an index -2.7 above 100 GeV/n. which is expected from a conventional leaky box model. although the statistics is not yet sufficient.
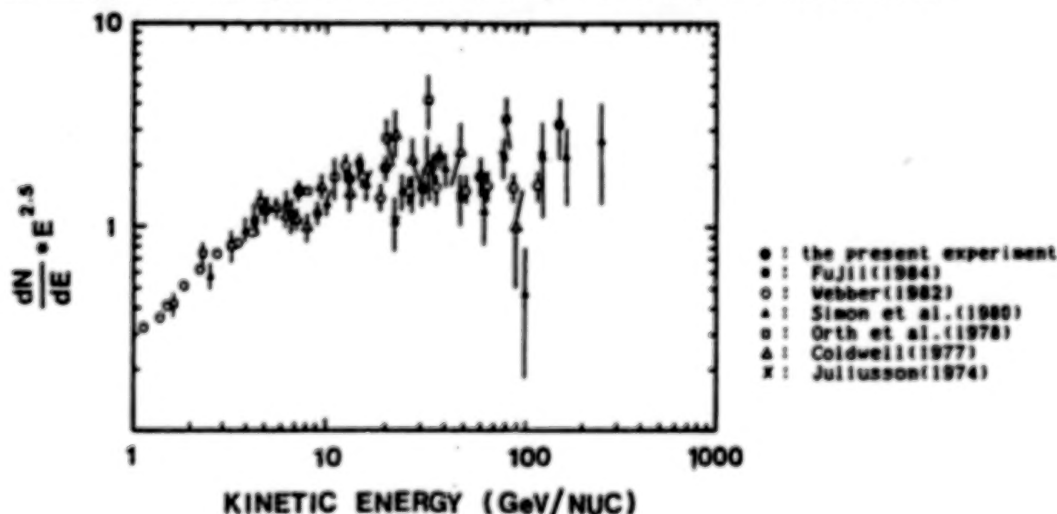
Fig.4 The iron spectra as compared with measurements of other values. The spectra have been multiplied by $E^{2.5}$ (kinetic energy) to emphasize differences. The intensities are in particles/m^2 str sec·GeV per nucleon and kinetic energy is in GeV per nucleon.

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MEASUREMENT OF THE IRON SPECTRUM FROM 60 TO 200 GeV PER NUCLEON

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1. <u>Introduction.</u> The high energy gas Cherenkov Spectrometer (HEGCS) was flown by balloon from Palestine, Texas on September 30, 1983. The instrument maintained an altitude of 118,000 ft. (4.7 g/cm^2) for 6 hours. Here we report details of the ongoing data analysis and preliminary results on the Fe spectrum up to 10^{13} eV/nucleus.

2. <u>Charge Measurement.</u> A description of the HEGCS instrument is given in the proceedings of the Paris ICRC (Streitmatter, et al., 1981)[1]. Incident charge is determined by measurement of the scintillation light which escapes from the 6 m^2 hodoscopes of scintillator triangles located in the top and bottom optical chambers. The escaped scintillation light is collected by 12 RCA 4525 PMT's externally located around the circumference of each chamber, giving two independent measurements of the charge.

Four corrections are made to these signals. (1) A cosine correction is made. Position of the incident cosmic ray as it passes through each of the two hodoscopes is determined from the relative size of signal from the three photomultipliers optically coupled to the struck scintillator triangle. The uncertainty in position is about ± 10 cm at present. (2) A correction for variations in scintillator thickness is made. As the cost of machining flat and polishing 12 m^2 of scintillator was prohibitive, the thickness of the hodoscope triangles was mapped. During assembly, an acoustic thickness gage was used to measure (± 0.001 inch) the thickness at 120 points on each of the 48 array triangles. Typically, thickness varies by ± 5 percent over a triangle. (3) The geometrically trapped scintillation light in a triangle has a small probability of escape at each internal surface reflection. The amount of such light escaping over the total triangle surface is a weak function of the position at which the cosmic ray is incident. A systematic correction of up to 12 percent is made for this effect. (4) The top and bottom diffusion chambers are not ideal white boxes. There are position dependent effects upon the relative amount of light collected by each of the twelve external photomultipliers. We are currently working on improvements in the correction of these effects. For charges above 16, the present σ/μ (resolution/mean) of the corrected PMT signals from each chamber is 0.069, corresponding to a charge resolution of 0.8 for Fe. The resolution is dominated by nonphotostatistical systematics.

3. <u>Cherenkov Signal.</u> Cherenkov light from the central gas volume was collected by 24 RCA 4522 photomultipliers located at the upper circumference of the drum. The signal from each PMT was separately digitized. The Freon-12 was kept at a pressure of 2.47 psi, corresponding to a Cherenkov threshold energy of 49 GeV/nucleon. In addition to the above-threshold gas Cherenkov light, incident nuclei at

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all energies above the Palestine cutoff made Cherenkov light in the
BaSO$_4$ white paint covering the inner surfaces of the upper and lower
pressure bulkheads. The Cherenkov light generated in the two painted
surfaces is about 14 percent of the saturated gas signal, displays a
cosine effect, and is statistically broadened in a manner indicating
that over the painted surfaces there is 20 percent variation in
effective emitting thickness of the BaSO$_4$. Figure 1, taken from flight
data, is a histogram of the "paint-light" signals to one 4522 PMT from
incident iron. The first and second photoelectron peaks are clearly
visible. Thus, the Cherenkov signals can be directly expressed in terms
of the number of photoelectrons collected. For an iron nucleus passing
vertically through the detector, the paint-generated Cherenkov light
results in an average of 51 photoelectrons, total, being collected. The
saturated ($\beta = 1$) gas signal from a vertical iron is best fit (see
below) as 370 total collected photoelectrons.

Because the 4522 PMT's are separately digitized, it is possible to
note individual PMT's struck by delta-rays. Typically, one PMT
saturates, while the average signal to the other PMT's is increased by
less than one photoelectron. The probability of events with a delta-ray
tube hit is a strong function of position, being greatest at the
periphery of the detector (radius 150 cm) near the PMT's. At the
largest radii, multiple delta-ray events can be seen. Although these
events can be recovered, we are presently making a conservative
geometric cut, restricting accepted events to be within 115 cm of the
center of the top hodoscope.

4. High Energy Data. In addition to the geometric cut, we require that
the top and bottom charge determination agree within two standard
deviations, and that the hodoscope signals be consistent with the
passage of a single particle through the detector. These restrictions
effectively eliminate fragmentations and nascent air showers. Figure 2
is a cross plot of Cherenkov signal versus charge. For plotting, a cut
has been made surpressing events with only "paint-light". The upward
fluctuating "paint-light" events appear as a band across the bottom of
the plot. For the purpose of analysis, iron is defined as those events
with determined charge between 24.7 and 27.7, corresponding to standard
deviations in signal of two and three, respectively. The larger
accryptance on the high side was made because of the tendency, seen in
Figure 2, of high Cherenkov events to deviate toward higher determined
charge. We attribute this trend to relativistic rise, but have deferred
a quantitative investigation pending improvement in the charge
resolution.

The maximum likelihood technique has been used to determine the
iron spectral index. The total Cherenkov signal in photoelectrons has
been modeled, including the statistical fluctuations from the paint-
generated and gas-generated photons. The number of photoelectrons
corresponding to the gas $\beta = 1$ point is a free parameter of the model.
The assumed spectra used as input to the model have been normalized to
the HEAO-3 (Lund, 1984)[2] iron data. That is, the modeled spectra are
assumed to attach to the HEAO iron flux at 25 GeV/nucleon and to be a
single-index power law above this energy. The index of the power law is
the second free parameter of the model. Making a low energy cut of

60 GeV/nucleon and calculating likelihoods from the data in Figure 2, we find that the best fit spectral index is 2.77 ± 0.12. The best fit value for the total number of photoelectrons from gas-generated photons from a vertical, β = 1 iron is 370. This indicates that the Cherenkov signal retains statistical power in energy discrimination up to about 215 GeV/nucleon.

Future improvement of the charge resolution and inclusion of the full geometric factor should allow improvement of the error in determination of the iron spectral index and sufficient statistics to determine the index of the iron secondaries.

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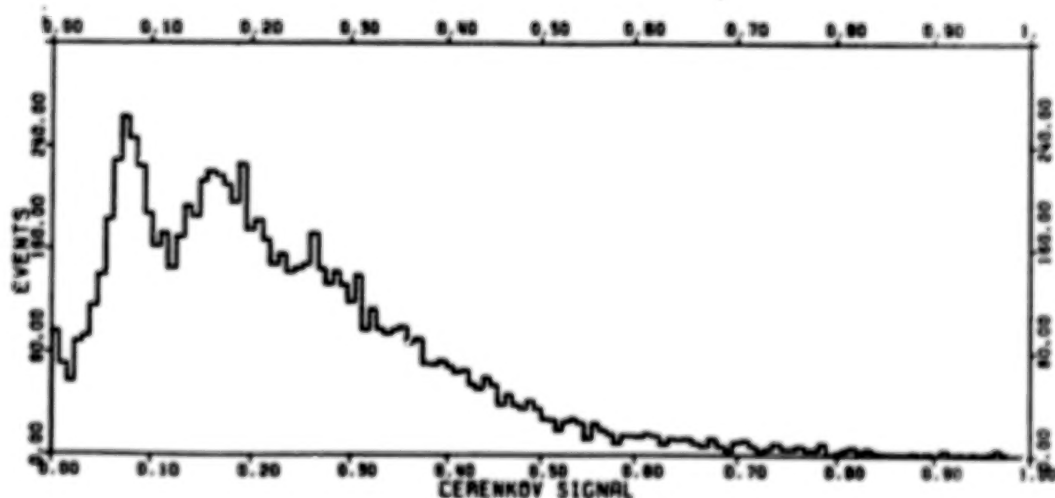
Figure 1
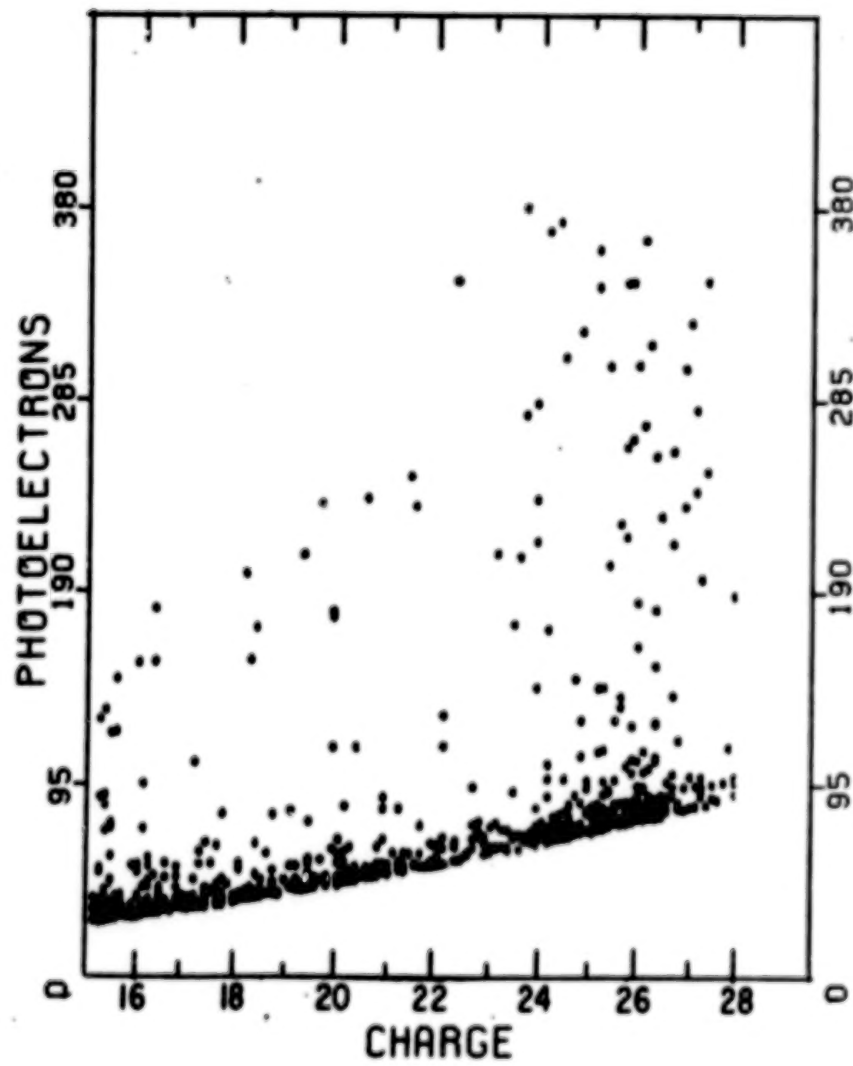
Figure 2

COSMIC RAY NUCLEI OF ENERGY > 50 GeV/NUC

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ABSTRACT

Preliminary results from the High Energy Gas Cherenkov
Spectrometer indicate that the sub-iron to iron ratio
increases beyond 100 GeV/nucleon. This surprising finding
is examined in light of various models for the origin and
propagation of galactic cosmic rays.

1. Introduction. The study of the composition of cosmic radiation and
its energy distribution has resulted in the development of several
models of cosmic ray propagation and information about sources and
acceleration phenomena (Cesarsky, 1980) [1]. The results from several
balloon experiments and the good statistics data from the HEAO-C
measurement (Englemann et al., 1985) [2] indicate that the matter
traversed by cosmic rays decreases with energy. In the energy range 1-
25 GeV/nuc, this dependence of matter traversed by cosmic rays is
expressed as $(rigidity)^{-0.6}$. This trend, if continued beyond 50
GeV/nuc, would result in matter traversed decreasing below 1 g/cm^2. As
the amount of matter becomes small, the effects of nuclear interaction
in the Interstellar Medium (ISM) become difficult to detect if the
nuclear mean free path (λ) in the ISM is much larger than 1 g/cm^2. For
Fe nuclei $\lambda = 2.8$ g/cm^2 and so relatively Fe becomes a more suitable
nucleus to study compared to C, O. The widely differing consequences
predicted by the leaky box, nested leaky box, and the closed galaxy
models could be tested by studying the relative amounts of primary Fe
nuclei and the secondaries from the breakup process.

In addition to these theoretical models, the results from the
experiments on the detection of antiprotons (Golden et al., 1979, [3]
Bogomolov et al., 1979, [4] Buffington et al., 1981) [5] suggest that
the matter traversed by cosmic ray protons may not be consistent with
cosmic ray propagation models derived from the study of heavy nuclei.
In this, we discuss some of the suggestive trends seen in the
preliminary data of the High Energy Gas Cherenkov Spectrometer (HEGCS)
and see what we can learn about the conflicting requirement of these
phenomena. Details regarding the HEGCS experiment and data analysis are
reported in the proceedings of the Conference (paper OG 4.1-11,
Streitmatter et al., 1985) [6].

2. Data in Fe and Sub-Fe Region. In the lower energy region up to 25
GeV/nuc, the HEAO-C (Englemann et al., 1985) [2] with its excellent
charge resolution and statistics gives a reliable data base. Beyond 25
GeV/nuc, several balloon experiments (Simon et al., 1980, [7] and
references therein, and Streitmatter et al., 1985) [6] provide data.
The very low flux of the particles to be detected is the most serious
problem for statistical reliability. Beyond a few hundred GeV/nuc, the
situation is even more murky. JACEE's (Burnett et al., 1983) [8]
finding that the highest energy particle was not an Fe but a Ca and the
absence of Fe nuclei up to a total energy of 10^{14} eV is in contrast with

the delayed particle EAS experiment of the Maryland group (Goodman et al., 1982) [9]. The Maryland group concludes that their results are consistent with a Fe spectrum with a power law exponent -2.39 ± .09. It is to be remembered, however, that EAS experiments have no charge resolution to discriminate between Fe primaries and secondaries of Fe.

In Figure (1) we show the preliminary results from HEGCS in the Fe and sub Fe group. The secondaries of Fe seem to cluster at either the low or high Cherenkov signal, with a paucity of points in between. Fe, however, seems to be distributed more uniformly throughout, with the number of points tapering off at the high signal limit.

Maximum likelihood estimates of the power law exponent for iron give -2.77 ± 0.12, in good agreement with the energy spectrum of protons and He nuclei, as obtained by Ryan et al., 1972 [10] and the JACEE group [9].

3. Double Diffusive Galaxy Model. We have considered a model which has characteristics of both the two component models previously discussed, the nested leaky box model (Cowsik and Wilson, 1973) [11] and the closed galaxy model (Peters and Westergaard, 1977) [12]. The model is characterized by two leaky boxes one inside the other as in the nested leaky box model. The observer is inside the inner box as in the closed galaxy model. Particles are held in both boxes by diffusive scattering and so both boxes would act like leaky boxes. The inner box represents the local interstellar region and the local sources. The lifetime of particles within this source region would be given by the ^{10}Be observations and the mean matter traversed would be that given by the HEAO-3 observations of B and C, N, O elements. The nuclei observed from a local source region would be relatively young. The composition consists of heavy nuclei.

The outer box would be the galaxy and its halo. This outer box would contain "old" particles, including protons and their secondary antiprotons. Particles would propagate therein under the control of a diffusion coefficient which has the same rigidity dependence as in the inner box, namely, scattering controlled by magnetic inhomogenieties. This would be required by the observation that the proton spectrum is assymptotically the same as those of the heavier nuclei, i.e., γ ~ 2.75. The matter traversed by particles in this outer box would have to be about three times that of the inner box. Since the mean density is much lower, the lifetime in the outer box would have to be 50-200 time longer than in the inner box.

The source spectra would be given by shock acceleration and the equilibrium spectra observed would be steepened by the energy dependent diffusion in both boxes. This model would remove any conflict between the low energy composition data and the high energy isotropy, which is determined by the conditions in the outer box. The 1 GeV/amu particles observed at Earth contain "young" heavy nuclei from nearby sources ($\le$ 0.5 kpc) and "old" protons and helium nuclei from the galaxy as a whole.
We may be effectively outside the source of the very lowest energy particles (~ 100 MeV/amu) because, at this low energy, the diffusion

coefficient will be very small. This could explain the increasing truncation of the path length distribution below 1 GeV/amu (Wefel et al.).

4. Discussion. Remembering that these results are preliminary, one can note that if iron secondaries do increase at high energies, the conventional leaky box with a monotonic decrease of matter with energy will need modification to account for the ratio of Fe secondaries/Fe at high energies. The antiprotons detected (Golden et al., 1979) [3] do need more matter traversal than the leaky box model would allow. Cowsik and Gaisser 1982, [13] postulate separate sources for antiprotons and heavy nuclei. The normalization of the strengths of these sources would depend on the relative amounts of antiprotons, secondary, and primary heavy nuclei. Various considerations of the nature suggest a two component model for the propagation of cosmic rays.

A leaky box like the outer box with a mean matter traversed would produce an iron secondary to iron ratio approximately twice that of a $7g/cm^2$ inner box, but both boxes produce a ratio which falls with increasing energy due to the energy dependence of the diffusion coefficient. It, therefore, seems to be difficult to find an admixture of the relative abundances of iron from the two components that could produce a sub-iron to iron ratio which would increase with energy unless the outer box contributes only at higher energy. This could be the case probably only if the relative size of the diffusion coefficient were contrived in the same manner.

In conclusion, it seems difficult to match the increase in the sub-iron to iron ratio with a shock acceleration model including a local source on a general galactic background without introducing a new parameter, namely, the variation of diffusion coefficient with position in the galaxy. Of course, the closed galaxy model itself requires source spectra which are as steep as proton spectrum. One variant of this model might be that high energy particles can penetrate into regions of dense matter. This is the functional equivalent of having a diffusion coefficient which is contrived in a manner which allows higher energy particles to pass through more matter.

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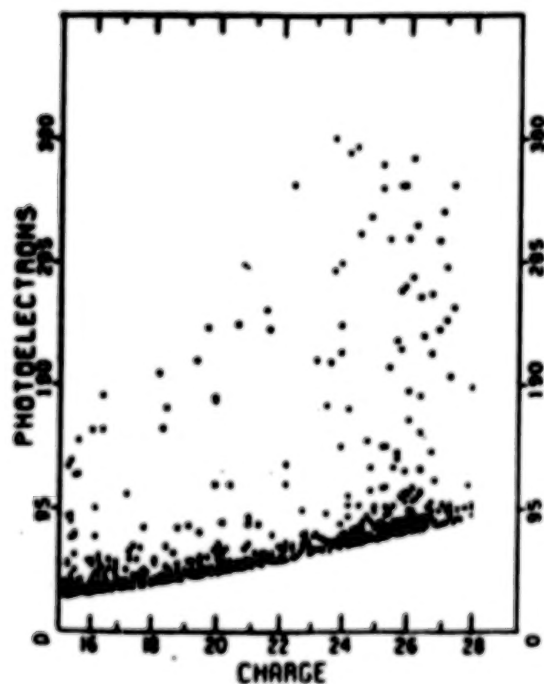
Figure 1

N85-34019

COMPOSITION AND ENERGY SPECTRA OF COSMIC RAY NUCLEI ABOVE 500 GeV/NUCLEON
FROM THE JACEE EMULSION CHAMBERS[+]

THE JACEE COLLABORATION[*]

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ABSTRACT

The composition and energy spectra of charge
groups(C - O), (Ne - S), and $(Z \geq 17)$ above 500
GeV/nucleon from the experiments of JACEE series
balloon borne emulsion chambers are reported.

1. Introduction.

Studies of cosmic ray elemental composition at higher energies
provide information on propagation through interstellar space, acceleration
mechanisms, and their sources. One of the present interests is the
elemental composition at energies above 100 GeV/nucleon. Statistically
sufficient data in this energy region can be decisive in judgement of
propagation models from the ratios of SECONDARY/PRIMARY and source spectra
(acceleration mechanism), as well as speculative contributions of differ-
ent sources from the ratios of PRIMARY/PRIMARY. At much higher energies,
i.e., around 10^{15} eV, data from direct observation will give hints on the
"knee" problem, as to whether they favor an escape effect possibly
governed by magnetic rigidity above 10^{16} eV.

The JACEE balloon flight experiments continue to measure composition
and energy spectra of cosmic rays (Z = 1 to 26) directly at energies 10^{12}
to 10^{15} eV using large area thin emulsion chambers [1 - 5]. The previous
JACEE results indicated no significant change of spectral indices up to
500 TeV and 50 TeV/nucleon for proton and helium spectra, respectively [4].
Flux values of each group (C - O), (Ne - S), and (Fe) at least up to
10^{14} eV also indicated no significant evidence for heavy nuclei dominance
within the limited statistics [5]. In this paper, the results for the

energy spectra of charge groups (C - O), (Ne - S), and ($Z \geq 17$) above 500 GeV/nucleon are updated.

2. Apparatus and Experimental Procedure.

Details of the apparatus and techniques of JACEE emulsion chambers have been reported in refs. [1 - 5]. Each detector, comprised more than 350 layers of materials, is functionally divided into three sections: (1) the primary charge determination module at the top, (2) the target module where nuclear interactions occur preferentialy (3) the calorimeter at the bottom to measure the energies of released gamma rays from interactions.

Events were detected by visual scanning of X-ray films for dark spots produced by electromagnetic cascades in the calorimeter under the same criterion of darkness (D) in an area of 200 x 200 μm^2. For these events, primary charge Z ($\Delta Z < 1$) above the interaction and the total energy of released gamma rays ΣE_γ ($\Delta \Sigma E_\gamma < 25$ %) were measured [1 - 5].

The maximum value of darkness (D_m) in the cascade development is a function of not only ΣE_γ but also the vertex height (H) from the top of the calorimeter, incident angle (θ), and interaction characterstics (transverse momentum and multiplicity). Among these parameters, the main factors are ΣE_γ and H. For a fixed ΣE_γ value, D_m distributes around some mean value. The width of this distribution $g(D_m)dD_m$ depends on the primary charge (mass) and the chamber design. $g(D_m)$ has been calculated by a Monte Carlo method using the chamber design adopted here, interaction characteristics (CKP and superposition models), and characteristic curves of the response of X-ray films. Then, the detection efficiency $P(Z, \Sigma E_\gamma)$ under the threshold D_m^{th} is calculated by,

$$P(Z, \Sigma E_\gamma) = \int_{>D_m^{th}} g(D_m)dD_m \Big/ \int_{D_m} g(D_m)dD_m .$$

In case of calorimeter jets, i.e., H = 0, $P(\Sigma E_\gamma)$ rapidly reaches 100 % at $\Sigma E_\gamma = 1$ TeV for all elements under the threshold level $D_m^{th} = 0.1$ which is a practical threshold, because of no fluctuation of H. On the other hand, in the case of target jets, the practical threshold D_m^{th} becomes about 0.15 and the width of $g(D_m)$ becomes larger due to a fluctuation of H values. This gives higher values of ΣE_γ to obtain $P(\Sigma E_\gamma) = 100$ %. The critical ΣE_γ values have been estimated by the above method for different nuclear species. For light elements such as proton and helium, the critical ΣE_γ was about 1.5 TeV which has been achieved in an analysis of selected JACEE chambers. Under the present standard event selection ($D_m^{th} = 0.3$) the detection efficiency $P(\Sigma E_\gamma \geq 10$ TeV) is confirmed to be 100 % for all elements and for all existing JACEE chambers.

3. Deconvolution of Primary Spectrum.

The observed ΣE_γ spectrum is a convolution of the primary spectrum and the distribution function $f(k_\gamma)$ where k_γ ($= \Sigma E_\gamma/E_0$) is a partial inelasticity into gamma rays; E_0 is primary energy. $f(k_\gamma)$ has been also calculated by the above Monte Carlo method [6], including succesive interactions, assuming its energy independence. The ΣE_γ spectrum $F(\Sigma E_\gamma)d\Sigma E_\gamma$ is given by,

$$F(\Sigma E_\gamma)d\Sigma E_\gamma = \int_{k_\gamma} f(k_\gamma)dk_\gamma \int_{E_0} G(E_0)dE_0 \, \delta(\Sigma E_\gamma - k_\gamma E_0) .$$

where $G(E_0)dE_0$ is primary spectrum. This formula directly shows that the ΣE_γ spectrum is uniquely a power law with the same index as the primary

spectrum when $G(E_0)dE_0 \propto E_0^{-\beta} dE_0$. The energy conversion factor Ck_γ from the ΣE_γ spectrum to primary spectrum is then given by,

$$Ck_\gamma = [\int_{k_\gamma} k_\gamma^{\beta-1} f(k_\gamma) dk_\gamma]^{1/(\beta-1)}$$

Ck_γ is applied to obtain the same flux between the ΣE_γ spectrum and the primary spectrum at $E_0 = \Sigma E_\gamma/Ck_\gamma$. Values of Ck_γ for each element in case of calorimeter and target jets were calculated as follows,

	P	He	N	Mg	Ca	Fe
calorimeter	0.240	0.174	0.100	0.082	0.064	0.058
target	0.222	0.159	0.120	0.117	0.115	0.115

for chambers mainly used in this work [7].

The collecting power of the detectors was calculated by a Monte Carlo method using both the geometric aperture and the probability of interactions for each element. Absolute fluxes above chambers were estimated considering the resolution function of ΣE_γ measurements which is an almost constant Gaussian type with a 25 % width in our case. After atmospheric correction at the depth of 3 - 5 g/cm^2, the flux values at the top of atmosphere were obtained.

4. Results and Discussion.

Figs. 1, 2, and 3 show the results of the integral energy spectra for groups (C - O), (Ne - S), and ($Z \geq 17$) above 500 GeV/nucleon under the present event selection criterion of D_u^{th} based upon a simulation. In Fig. 3, Fe spectrum at energies 20 to 80 GeV/n from the JACEE-3 hybrid detector experiment [8] is also shown. In these figures, the low energy results from two experiments [9, 10], recently reported, are included for comparison. Solid lines are the extrapolation from the flux value at 25 GeV/n of ref. [9] with the spectral indices 1.7 and 1.5. Data around 4 TeV/n for (C - O) and (Ne - S),and those around 1 TeV/n for ($Z \geq 17$) are corrected, by empolying the Monte Carlo calculations for data analysis below the sub-threshold ΣE_γ = 10 TeV. In these figures, at energies higher than sub-threshold, data of each group indicate slightly higher flux values (to about one s.d. from the extrapolated spectra with an index 1.7) with the statistics of only 4, 2, and 1 of 3 (Ca at 78 TeV/n) events for respective groups, while (C - O) data around 1.5 TeV/n with the statistics of 10 events are in agreement with the low energy data for index 1.7. Statistical improvements are obviously desired for our continueing efforts at the highest energies above 10^{14} eV.

Can emulsion chamber technique identfy a bending of the primary spectrum by using of the ΣE_γ method under the convolution of k_γ distribution? Monte Carlo studies have shown a positive answer for this question, at least for heavy nuclei component. If materials of more than about 3 interaction length are available, then the distribution function $f(k_\gamma)$ approaches the Gaussian type with about 35 % width, by virtue of succesive interactions. Hence, it is sufficient to detect any narrow peaks or bends in the energy spectrum, provided sufficient statistics are gathered. For observations above 10^{15} eV, however, the energy resolution becomes poorer than our current observations, because the shower maximum of electromagnetic cascades in the calorimeter becomes too deep for thin chambers currently adopted. Even in this case, emulsion chamber techniques still

provide measurements of cosmic ray energy above 10^{15} eV without increasing the thickness of calorimeter if the $e^{\pm}$ pair method is used to augment the ΣE_γ energy determination [11].

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Fig. 1

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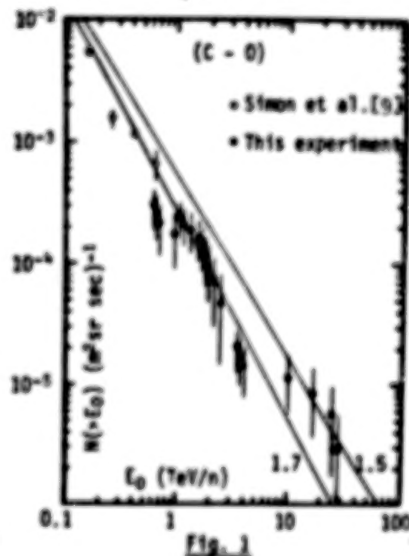
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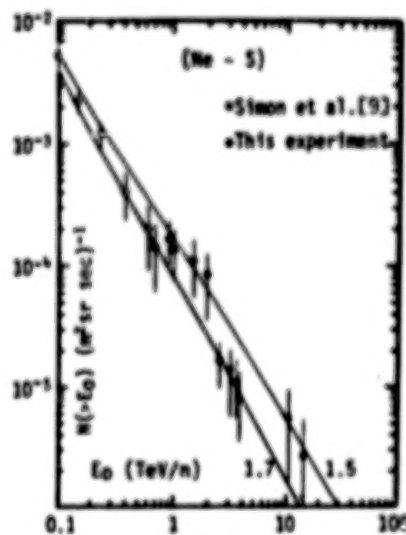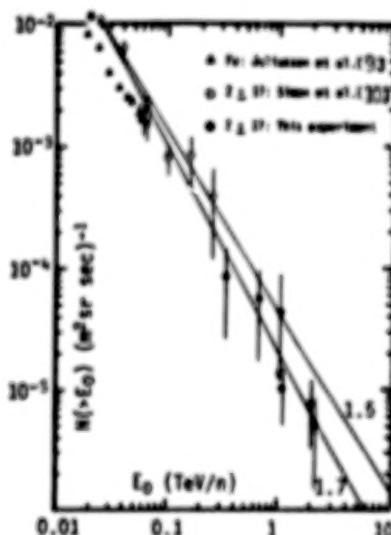
Fig. 3

CHARGE COMPOSITION AND ENERGY SPECTRUM OF COSMIC RAY PRIMARY PARTICLES FOR ENERGIES HIGHER THAN 1 TeV

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ABSTRACT

Onboard the "Cosmos-1543" satellite an experiment was performed to investigate the charge composition and primary cosmic ray energy spectrum for energies higher than 1 TeV. Preliminary experimental data are reported.

1. Introduction. Investigation of the energy spectrum of various groups of primary cosmic ray nuclei in the high and superhigh energy regions is one of the most important problems of cosmic ray physics and astrophysics. In the energy range 1-10 GeV per nucleon the situation is rather clear [1], while in the range of $E > 100$ GeV per nucleon the problem is not solved yet [2]. To perform investigations in this energy region we have elaborated a special apparatus [3] and carried out in 1984 the experiment beyond the atmosphere.

2. Methods. We used as energy detector the ionization calorimeter with the total thickness of absorber 5.5 paths for proton interaction. It consisted of 8 steel plates each 10 cm thick and located above 8 scintillators. Each scintillator was attached to a light-guide and viewed by a FEU-84. The calorimeter is situated below the aluminium target about 8 cm thick, two lead absorbers 3 cm and 2 cm

thick, and two rows of scintillators employed to estimate the energy of electromagnetic cascades generated in the target.

Above the installation two types of Cerenkov charge detectors are located. The first-type detector consists of II directed action counters. Each counter comprises a radiator in optical contact with a PMT-49 and measures charges in the range of $I \leq Z \leq 5 \div 7$. Above this detector the second one is located, which composed of four counters to measure charges in the range of $3 \leq Z \leq 60$. Every counter consists of a radiator enclosed in a light-proof box and is viewed by a PMT--49. An accuracy of determination of Z under onground conditions is about 4%.

The device comprised the total of I99 amplitude analysers serving 95 detectors. The device's construction, characteristics, stability, and energy consumption are described in detail in $[3]$.
3. Results. The device was exposed in an almost circular orbit with a mean removal from the Earth of 330 km and an inclination angle of 62.8°. It was oriented along three axes with the longitudinal axis being vertical.

The main mode for the device to put into operation required a signal in the directed action Cerenkov detector excited by a particle of $Z \geq I$, the total energy release in the calorimeter being $\geq I.5$ TeV at energy release ≥ 35 GeV at least in eight absorbers. The rate of event registration remained constant during the whole experiment. The performed analysis showed that all the experimental apparatus work had been stable.

Up to date a small fraction of the data obtained has been processed, and the material presented below is mainly qualitative.

Figs. I and 2 show the examples of registered events. Two projections of the device and the avalanche position in the calorimeter are shown. The height of rectangles is proportional to the particle number in the corresponding scintillator. In the topr part of the position of the operated charge detectors is shown. The first event was initiated by a proton with energy I5 TeV and the second one by a neon nucleus of energy 20 TeV.

Fig. 3 characterises the separation of both proton and helium

Fig. I
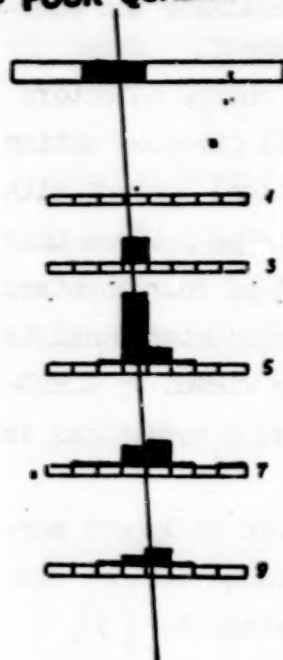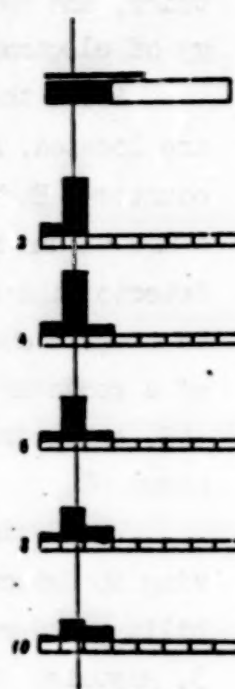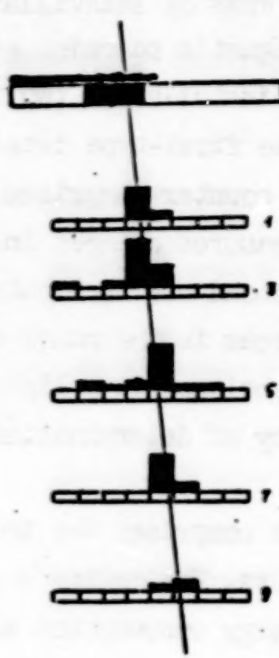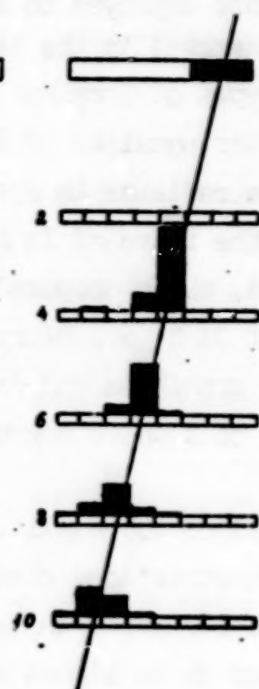
Fig. 2
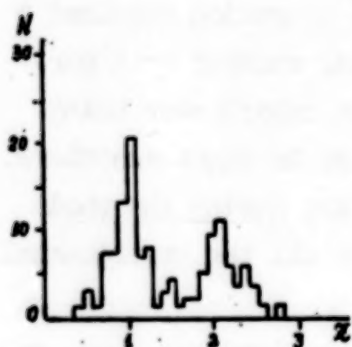
Fig. 3

of both proton and helium nuclei by the directed action charge detectors. The ratio of particles with $Z = 2$ and $Z = I$ (0.6-0.7) is close to that of at low energies.

The charge distribution at $Z \geq 5$ obtained with the aid of the upper detector is shown in Fig.4, alongside with the expected distribution, provided that the distribution on Z is the same as that of the lower energies, and the amplitude distribution at fixed Z is characterized by the rms spread $\sigma \approx 4\%$. An examination of Fig. 4 shows that at $Z \geq 5$ the nucleus charge composition is, within error limits, the same as that of at low energies.

Fig. 5 presents the differential spectrum of nuclei with $Z \geq 2$. At low energies the spectrum is limited by $E_{thr} \approx I.0 \div I.5$ TeV, and at higher energies $\gamma = 2.50 \pm 0.25$.

C - 2
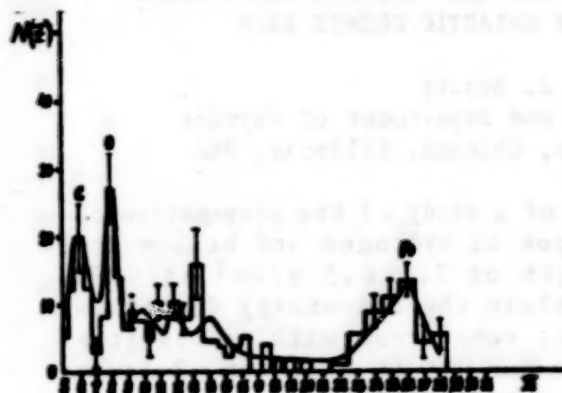
Fig. 4
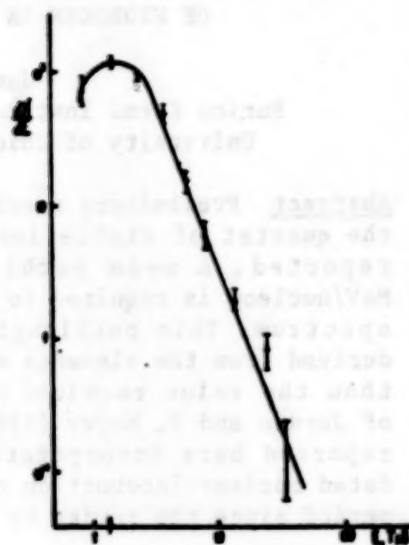
Fig. 5

Conclusions. It shoud be noted that the above presented experimental data do not indicate any abrupt variations of the spectrum and charge composition, however, they require further clarification. The presented distributions were plotted for all the events processed, while the threshold energies and the possibilities of particle registration may be a function of Z.

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N85-34021

INTERSTELLAR PROPAGATION AND THE ISOTOPIC COMPOSITION OF HYDROGEN IN THE GALACTIC COSMIC RAYS

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Abstract Preliminary results of a study of the propagation of the quartet of stable isotopes of hydrogen and helium are reported. A mean pathlength of 7.5 ± 0.5 g/cm^2 at $\sim$300 MeV/nucleon is required to explain the low-energy deuterium spectrum. This pathlength is consistent with pathlengths derived from the elements with Z>2, but is a factor $\sim$2 lower than the value required to explain the (^{3}He/^{4}He) measurement of Jordan and P. Meyer (1984). The propagation calculations reported here incorporate the preliminary results of an updated nuclear-interaction cross section survey covering the period since the review by J.P. Meyer (1972).

Introduction. The quartet of isotopes of hydrogen and helium constitute a closely-coupled set of nuclides which provide strong constraints on the cosmic ray source spectra and on the escape pathlength of cosmic rays from the galaxy. (See Simpson (1971) for a review.) The recent measurements of (^{3}He/^{4}He) in the energy range 5-10 GeV/nucleon by Jordan and P. Meyer (1984) and Jordan (1985) require a pathlength of $\sim$15 g/cm^2 to account for the experimental data, which is inconsistent with the value $\sim$6 g/cm^2 inferred from CNO and their secondaries. (e.g. Garcia-Munoz et. al. (1981)) In this paper, the pathlength traversed by low-energy H and He during interstellar propagation is studied using the high-resolution, low energy spectra of ^{1}H, ^{2}H and ^{4}He determined using the University of Chicago IMP-8 telescope under solar minimum (1976-1977) conditions (Beatty et. al. 1985 and references therein). It is found that the observed fluxes of these nuclei at low-energy are consistent with the pathlength deduced from the elements with Z>2, but not with the much longer pathlengths required by the high energy He isotopic ratio.

Measurements. The ^{2}H measurements used in this work were obtained using the University of Chicago IMP-8 telescope during the period June 1976 to April 1977, at solar minimum modulation. ^{2}H is identified by the (dE/dx) vs. residual E method. The measurement of ^{2}H is most reliable near the end-of-range, where the ^{2}H energy deposit in the CsI(Tl) residual E detector (D4) is $\sim$30% greater than the largest energy deposited by the more abundant ^{1}H (Figure 1,insert).
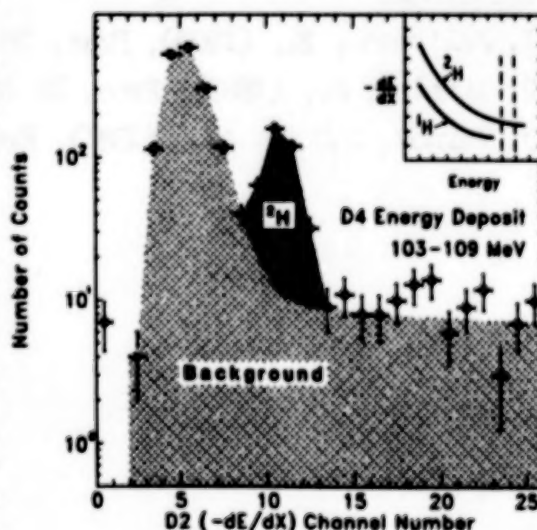
Figure 1

Plotting the number of counts per (-dE/dx) channel (D2), the ^{2}H appears
as a peak superposed on a high energy interaction background. At solar
minimum, subtraction of this background leads to a correction of only
25%. The r.m.s. width of the ^{2}H peak is 0.13 amu, corresponding to a FWHM
of 0.31 amu. A more detailed discussion of the data analysis has been
presented in Beatty et. al. (1985).

<u>Modeling of Cosmic Ray Propagation.</u> The effects of interstellar propaga-
tion on an assumed cosmic ray source spectrum are computed using a
weighted-slab model (WSM), in which solutions of the equation describing
the passage of nuclei through interstellar matter

$$\frac{\partial J_i}{\partial x} = \frac{\partial}{\partial E}(\frac{dE}{dx}J_i) + \sum_k \int \frac{J_k}{\Lambda_{ki}} dE' - \frac{J_i}{\Lambda_i}$$

are weighted by a pathlength weighting function (PLWF) to obtain the lo-
cal interstellar cosmic ray flux:

$$J_{c.r.}(E) = \int dx\ P(E,x)J_{slab}(E,x)$$

For a leaky-box model (LBM) with energy-independent escape pathlength ,
it can be shown that the PLWF is an exponential: $P(x) = exp(-x/\lambda)$.
(Lezniak,1979)

The calculation procedure used in this work includes the effect of
ionization energy loss at all energies, and includes kinematic energy-
changing effects in the reactions $H(p,d\ \pi^+)$ and $He(p,d)$ He. Kinematic
effects in other reactions and energy losses due to elastic scattering
are small and have been neglected. Results of calculations including the
small effects neglected here will be published elsewhere (Beatty, 1985).

The nuclear interaction cross sections used here are the prelimi-
nary result of a survey in this laboratory of the experimental cross
section measurements performed since the
compilation by J.P. Meyer (1972). The
remaining uncertainties in the cross sections
are largest for the production of deuterium by
the spallation of cosmic ray helium on the in-
terstellar medium at energies above 500 MeV
per nucleon.

Solar modulation has been taken into ac-
count using the model of Evenson et. al.
(1983). For the solar minimum data discussed
here, the adiabatic deceleration parameter
is 440 MV.

<u>The Primary Energy Spectra.</u> In the leaky box
propagation model, the local interstellar
spectra of ^{1}H and ^{4}He are simply related to
the source spectrum and to the functional form
of $\lambda(E)$. The pathlength for nuclear inelas-
tic interaction with the interstellar medium
is long compared with the expected escape
pathlength. Secondary production of these
species can be neglected because of their
large source abundances. Energy loss effects
are less important than for heavier elements:
the lowest energy local interstellar particles
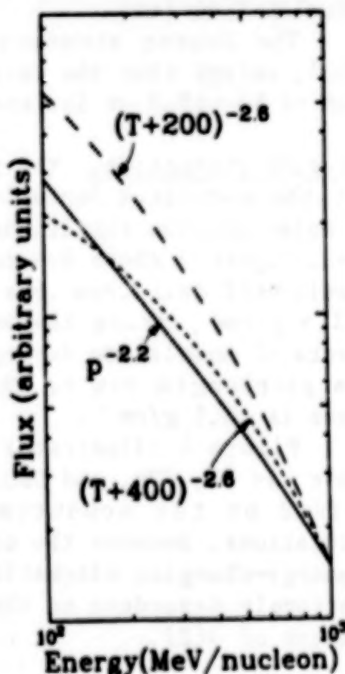
Figure 2

which are seen at Earth (i.e., which have local interstellar energies greater than the energy lost during solar modulation) have lost <20% of their initial energy during interstellar propagation. Under these conditions, the leaky box model solution can be approximated by the simple algebraic result $J(E)= \lambda(E) Q(E)$. In this paper, momentum power law source spectra of the form $\frac{dN}{dP} = \frac{dJ}{dT} \propto p^{-\gamma}$ have been used. Figure 2 compares the chosen source spectrum $p^{-2.2}$ with the spectra $(T+200MeV)^{-2.6}$ used by

Figure 3 Computed 1 A.U. H, H, and He spectra for a 7.5 g/cm pathlength under 1976-1977 solar minimum conditions. Panel (a): open circles, protons; filled circles, helium; Garcia-Munoz et. al. (1977). Panel (b), deuterium: filled circles, Beatty et. al. (1985); crosses, Webber and Yushak (1983); upper limits, Leech and O'Gallagher (1978).

J.P. Meyer (1974), and $(T+400MeV)^{-2.6}$ used by Garcia-Munoz et. al. (1981). The latter two spectra lead to a spectrum which is too steep when the energy dependence of $\lambda(E)$ at high energies is taken into account, but are similar to the momentum power-law spectrum above at energies below several GeV/nucleon.

The source abundances used in this work are those of J.P. Meyer (1985), except that the ratio $^1H/^4He$ at constant energy/nucleon is determined to be ~ 12.2 at low energy.

Deuterium Production. The pathlength is determined by the requirement that the modulated deuterium flux at 1 A.U. match the value measured under solar minimum conditions by the University of Chicago telescope on IMP-8. Figure 3 shows the computed ^1H, ^2H, and ^4He spectra together with experimental data from this period. (See caption) The pathlength required is 7.5 g/cm², using the model of Evenson et. al. (1983) to describe the effects of modulation during the 1976-1977 solar minimum. The error in this pathlength due to the experimental uncertainties in the measured fluxes is 0.5 g/cm².

Figure 4 illustrates the relative importance of contributions from cosmic ray ^1H, ^4He, and CNO. The local interstellar spectrum has been divided by the momentum power law source spectrum used in the calculations. Because the contribution from cosmic ray ^1H is entirely due to energy-changing kinematic processes, the importance of these reactions is strongly dependent on the source spectral form and on the low-energy behavior of $\lambda(E)$.

Difficulties in the inter-
pretation of weighted-slab models
arise when energy-changing
processes become important. Lezniak
(1979) has compared the LBM to the
WSM, and has noted cases in which
the mean of the WSM exponential
PLWF and the value of the LBM es-
cape pathlength are not equivalent.
We have investigated the importance
of these effects on the quartet.
For the case where $\lambda(E)$ increases
with increasing energy as $E^{0.5}$
(Garcia-Munoz et. al. 1981; Ormes
and Protheroe 1983), the effect of
ionization energy loss will in-
crease ^2H production by $\sim 5\%$, and
the effect of energy-changing
processes involving cosmic ray ^1H
will increase ^2H by $\sim 10-20\%$. It
should be noted that in both cases
the WSM

Figure 4

underestimates the production of ^2H relative to the corresponding LBM,
and therefore overestimates the pathlength traversed in the case where
$\lambda(E)$ increases with increasing energy. The quantitative analysis of the
case of energy-dependent PLWFs will be published elsewhere (Beatty,
1985).

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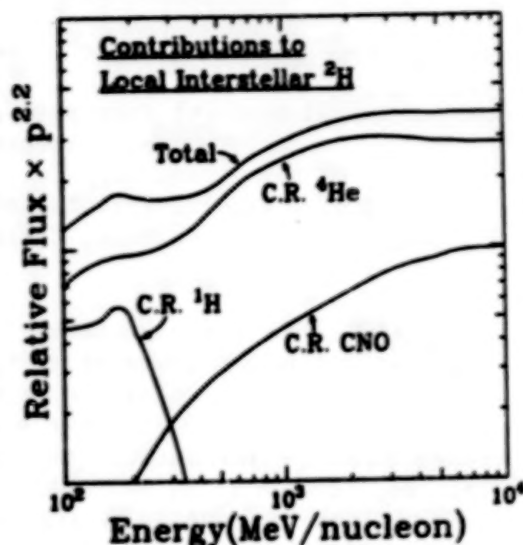
MEASUREMENTS OF GALACTIC HYDROGEN AND HELIUM ISOTOPES FROM 1978 THROUGH 1983*

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ABSTRACT. We have measured the differential flux of the hydrogen and helium isotopes using our instrument on the ISEE-3 spacecraft during solar quiet time periods from August 1978 through December 1983. These measurements cover the energy range from 26 MeV/nucleon through 138 MeV/nucleon for both ^1H and ^4He, from 24 to 89 MeV/nucleon for ^2H, and from 43 to 146 MeV/nucleon for ^3He. During the observations, the level of solar activity varied from near minimum to maximum conditions causing the observed flux of galactic cosmic rays to modulate by an order of magnitude. To describe the propagation in the galaxy, we find that the standard leaky box approximation with an escape path length of 6.7 g/cm^2 forms a self-consistent model for the light cosmic ray nuclei at the observed energies.

1. INTRODUCTION. Both cosmic ray ^2H and ^3He are secondary particles resulting from spallation of primary cosmic rays on interstellar matter. Measurements of the local flux of these particles are particularly interesting because the light cosmic rays have a path length for nuclear destruction which is greater than the mean confinement path length in the galaxy. Therefore, they are sensitive to the average amount of matter penetrated by the cosmic rays but not to details of the path length distribution.

We present here new measurements of the hydrogen and helium isotopes ^1H, ^2H, ^3He, and ^4He (the "quartet") made with the University of Chicago experiment on the ISEE-3 spacecraft. Although this instrument was primarily designed to observe the electron component, it achieves excellent isotopic resolution of the light nuclei, and permits reliable background determination over the energy range of nuclei stopping in the detector. A complete description of this instrument is given by Meyer and Evenson [1]. Isotopic resolution is achieved using the standard ΔE vs. E method. Details of the analysis procedure will be given by Kroeger [2]. We achieved a mass resolution of approximately ±0.34 amu FWHM (see figure 1).

2. RESULTS. The abundance ratios of secondary to primary particles are presented in figure 2. The average ratios are $^2H/^4He$=0.127±0.006 (65-87 MeV/n), $^3He/^4He$=0.075±0.008 (65-87 MeV/n), and $^3He/^4He$=0.074±0.005 (87-120 MeV/n). These ratios are not affected by anomalous helium fluxes
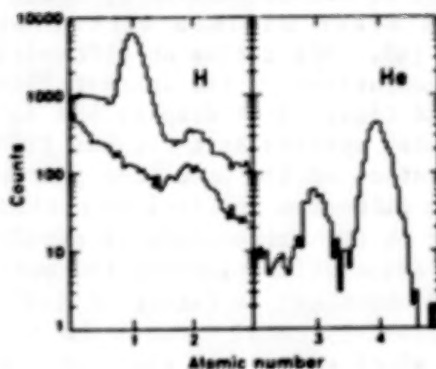
Figure 1

Mass histograms showing the isotopic resolution of the ISEE-3 instrument. The data were collected in 1979 in an energy range of 65-87 MeV/n for both ^2H and ^3He. The two hydrogen histograms are from using different detectors for the ΔE measurement. The bottom curve is composed of events classified as ^2H by the upper curve. Note the effective elimination of the structured background due to protons.

since these are significant only below 60 MeV/n. Calculations of solar modulation indicate that these ratios should vary by a factor of 1.26 for $^2H/^4He$ (top panel) with the lowest ratio occurring in 1978 and the highest in 1981. The $^3He/^4He$ ratio should vary by 1.15 in the same manner (bottom two panels). The modulation effects are within the statistical errors of our measurements.

3. DISCUSSION. The abundance ratios are interpreted using a leaky box approximation for the confinement of cosmic rays in the galaxy. In this model effects due to interactions with the interstellar medium are included (i.e. energy loss due to

Figure 2

ionization, nuclear destruction and production). It is assumed that the source spectrum of cosmic rays is a power law in rigidity with a spectral index of -2.2, and that the mean escape path length is given by,

$$\Lambda_e = \begin{cases} X & \text{for } R < 5.5 \text{ GV} \\ X \left(R / 5.5 \right)^{-0.6} & \text{for } R > 5.5 \text{ GV,} \end{cases}$$

where R is rigidity and X is the mean escape path length. We determine the path length X which best fits our data.

During our measurements, solar activity changed from near minimum conditions to solar maximum. Consequently, the flux of galactic particles changed by an order of magnitude as measured at 1 AU. We account for modulation using a spherically symmetric convection diffusion model [3]. This model requires a suitable choice of the diffusion coefficient for particles in the heliosphere in order to simulate particular levels of modulation. The selection we make enables us to match the local interstellar ^4He spectrum calculated from the leaky box model to our
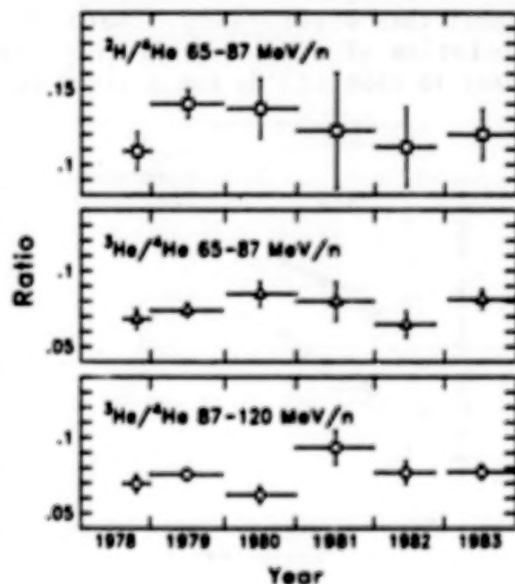
measured data. The diffusion coefficient we use is derived by inter-
polating between the solar maximum and solar minimum diffusion
coefficients obtained from Garcia-Munoz [4]. His choice of diffusion
coefficients were gained originally from a comparison of the interstellar
electron spectra with local measurements. In figure 3 we display the lo-
cal interstellar ^{4}He spectrum and the modulated spectra that fit our 1978
and 1981 data. Figure 4 compares our calculation of the modulated proton
spectra with the measurements using the same diffusion coefficients that
were determined from the ^{4}He fit. The fit to the proton data is excel-
lent for the years 1978-1980. However, the calculation predicts too many
protons for the years when modulation is strongest (a factor of 1.3).
This apparent discrepancy can easily be resolved by small changes in the
assumptions used in the leaky box model which effect the shape of the
calculated interstellar spectra. However, rather than introduce addi-
tional free parameters we prefer to use the simplest model possible and
neglect this discrepancy. Both ^{2}H or ^{3}He are expected to follow the
modulation of ^{4}He more closely than protons since their rigidities are
closer to that of ^{4}He for a given energy/nucleon.
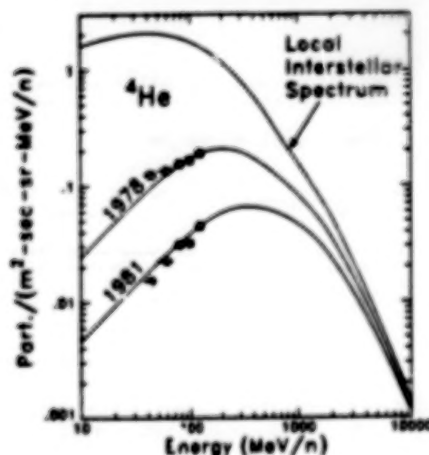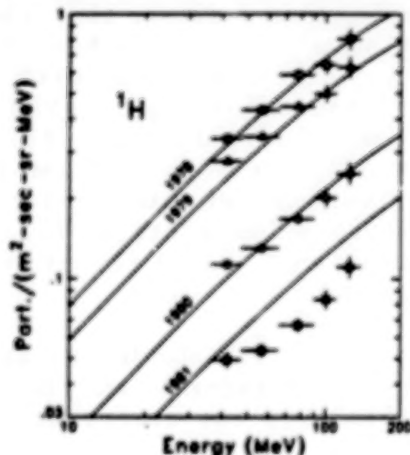
Figure 3   *Figure 4*

All of the parameters in the propagation and modulation models have
been either specified or determined except for the mean escape path
length, X. Figure 5 shows our calculation of the ^{2}H/^{4}He ratio as a func-
tion of energy for various path lengths X. The shaded region in this
figure represents the range of variability caused by changing solar
modulation. The upper side of the shaded region results from modulation
for 1981. We compare our measurements (closed circles) with other recent
measurements (open symbols, references 6-10) in this figure. Figure 6 is
a similar display, but for the ratio ^{3}He/^{4}He.

The mean path length X that best fits our measured abundance ratios
is 7.6 ± 0.4 g/cm^2 for the ^{2}H/^{4}He ratio (65-87 MeV), 6.0 ± 0.3 g/cm^2 for the
^{3}He/^{4}He ratio (65-87 MeV), and 5.6 ± 0.2 g/cm^2 for the ^{3}He/^{4}He ratio (87-
120 MeV). These ratios are weighted averages of the results from all six
years. The difference between the best fit path length for H and He
may be due to uncertainties in the production cross sections [5] used in
this calculation. The mean between the two determinations is ap-
proximately X=6.7 g/cm^2.
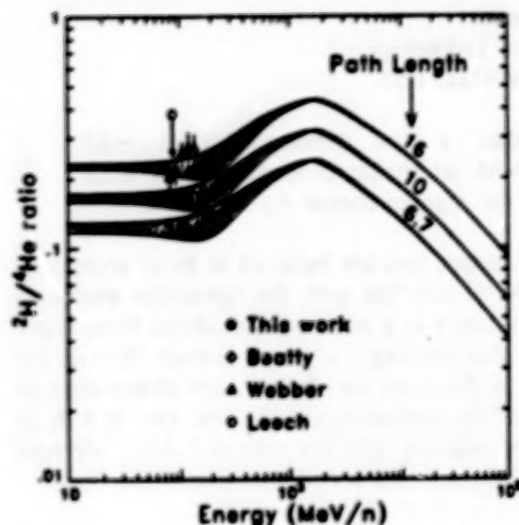
Figure 5
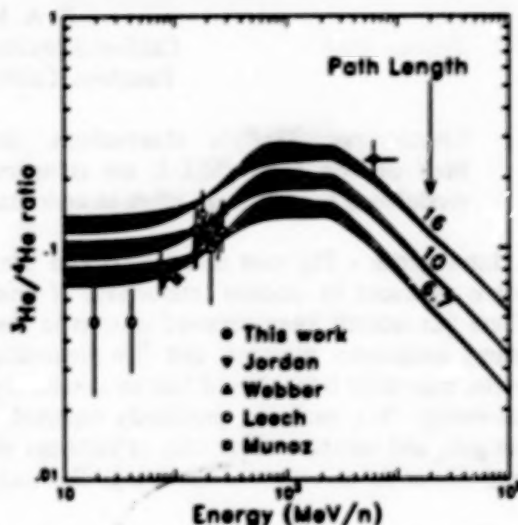
Figure 6

4. **CONCLUSION.** Our measurements of the spectra and fluxes of ^1H, ^2H, ^3He, and ^4He can be fit using a standard leaky box model for galactic cosmic ray confinement. This model is essentially the same as that used by other authors to fit the B/C ratio with a similar leakage path length [11,12]. This model has also been successful in explaining the abundances of iron secondaries at higher energies [13].

5. **ACKNOWLEDGEMENTS.** We would like to thank L. Krawczyk and C. Sethuraman for their valuable assistance in data processing and reduction.

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Cosmic Ray ³He Measurements

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Cosmic ray ³He/⁴He observations, including a new measurement at ~65 MeV/nucleon from ISEE-3, are compared with interstellar propagation and solar modulation models in an effort to understand the origin of cosmic ray He nuclei.

1. Introduction - The rare isotopes ²H and ³He in cosmic rays are believed to be of secondary origin produced by nuclear interactions of primary ¹H and ⁴He with the interstellar medium. There has recently been renewed interest in these isotopes as a result of indications from high-energy antiproton, positron, and ³He observations that the origin of some primary H and He nuclei may differ from that of heavier cosmic rays. In this paper we report a new observation of low-energy ³He, examine previously reported ³He/⁴He measurements at both low and high energies, and compare these with calculations of the expected ³He/⁴He ratio at 1 AU. We find no evidence for an excess of low-energy ³He such as that reported at high energies.

2. Observations - The new observation reported here was made with the Caltech Heavy Isotope Spectrometer Telescope (HIST) on ISEE-3 (now renamed ICE) during quiet-time periods from 8/13/78 to 12/1/78. Figure 1 shows the He isotope distribution from the two highest energy intervals covered by HIST. This data results in a ³He/⁴He ratio of 0.066±0.016 from 58 to 77 MeV/nucleon. Some of the ⁴He in this energy interval is "anomalous" cosmic ray (ACR) ⁴He, which has been corrected for using a decomposition of the ACR and galactic cosmic ray (GCR) fluxes [1], and their time history. The derived correction factor of 1.12±0.06 results in an "observed" GCR ³He/⁴He ratio of 0.074±0.018.
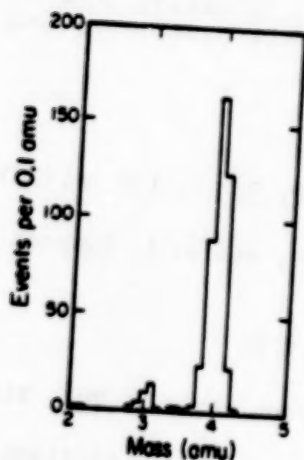
Figure 1: The distribution of quiet-time ³He (48 to 77 MeV/nucleon) and ⁴He (41 to 67 MeV/nucleon) observed by the Caltech experiment on ISEE-3 during late 1978.
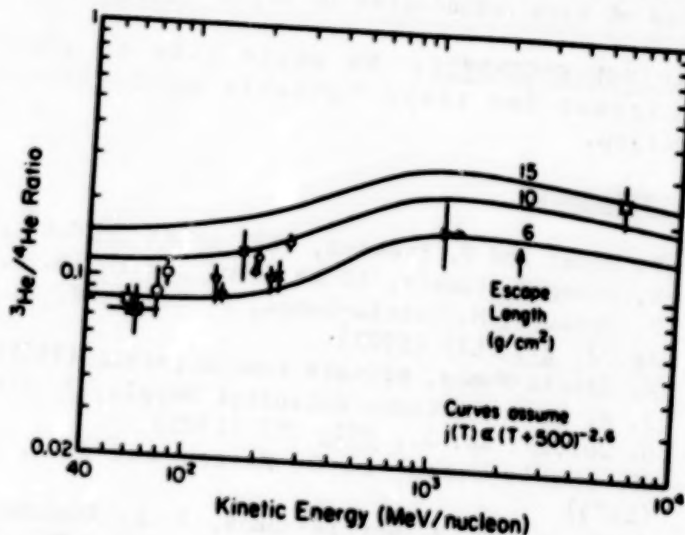
Figure 2: Measured and calculated ³He/⁴He ratios. Spacecraft observations: ■ This work, 1978; □ Goddard-UNH, 1972 [2]; O Chicago, 1973-1974. Balloon data: ▽ Rochester, 1966 [5]; △ UNH, 1972 [6]; X UMd., 1972 [7]; ◇ UNH, 1977 [8]. Geomagnetic method: ▷ Ioffe, 1976 [11]; ⋈ Chicago, 1981 [9,10].

Figure 2 shows our new measurement along with selected other ^{3}He/^{4}He observations. The spacecraft observations [2,3,4] are from the 1972-1978 solar minimum period and are limited to the 50 to 100 MeV/nucleon interval where contamination by ACR ^{4}He is minimized. Since the reported observations include ACR ^{4}He, each has been corrected as described above. Figure 2 also includes observations from ~100 to 300 MeV/nucleon by balloon-borne instruments [5,6,7,8] (here referred to as "the balloon observations"). As discussed in the Appendix, we believe that the observations as reported (and as plotted in Figure 2) have not adequately corrected for ^{3}He produced in the atmosphere, and a proposed correction (typically ~16%) is therefore applied in subsequent Figures. At >300 MeV/nucleon the only observations use the geomagnetic method, including the recent Jordan and Meyer (J&M) measurement at ~6 GeV/nucleon [9,10], and an earlier result [11]. These experiments also fly on balloons, but are not subject to the same atmospheric corrections.

3. Interpretation of ^{3}He/^{4}He Observations - To interpret the available ^{3}He/^{4}He data we use propagation calculations by J. P. Meyer [12], who calculated *interstellar* spectra for ^{1}H, ^{2}H, ^{3}He, and ^{4}He for a variety of source spectra and mean pathlengths, using the standard "leaky-box" propagation model. The source spectra were of the form $dJ/dT \propto (T + U)^{-2.6}$, where T is kinetic energy per nucleon and $0 \leqslant U \leqslant 938$ MeV/nucleon. We calculated the effects of solar modulation on these spectra using the solar-minimum form of the interplanetary diffusion coefficient from Cummings et al. [13] and numerical solutions of the Fokker-Planck equation including the effects of diffusion, convection, and adiabatic deceleration. Results of these calculations are shown in Figure 2 for source spectra with U=500.

By comparison with the calculations (e.g., Figure 2) each observation determines a "leaky-box" escape-length (λ_e), as shown for U=500 spectra in Figure 3. Note that the spacecraft and (corrected) balloon observations all favor $\lambda_e \approx 6$ to 7 g/cm^2; only the J&M measurement at ~6 GeV/nucleon indicates $\lambda_e \geqslant 10$ g/cm^2. Table 1 summarizes the mean escape-lengths obtained. Note that the proposed atmospheric correction (see Appendix) lowers the mean escape-length for the balloon observations by ~1.6 to 1.9 g/cm^2 (depending on the spectrum), and generally improves agreement with the spacecraft observations. Table 1 indicates that softer source spectra (e.g., U=200) lead to a somewhat greater λ_e at low energies. This is both a propagation effect (see [12]), and a result of the increased solar modulation required for soft spectra.

4. Discussion - We wish to determine whether the ^{3}He observations are consistent with the propagation/modulation models derived for heavier nuclei, or whether there is evidence for He nuclei with a separate origin and/or history. For the J&M measurement at ~6 GeV/nucleon we find a pathlength of ~15±6 g/cm^2 (in agreement with their value), independent of the assumed source spectrum. This value is significantly greater than derived from the B/C or other Z$\geqslant$3 secondary/primary ratios, which imply $\lambda_e \approx 5.5$ g/cm^2 at ~6 GeV/nucleon [14]. Thus, if the J&M measurement (and its interpretation) is correct, it does imply a high-energy ^{3}He excess, and a different origin for at least some high-energy He nuclei.

Figure 3: Plot of the escape length determined by the observations in Figure 2. The mean and uncertainty of the spacecraft (S), corrected (BC), and uncorrected (BU) balloon observations are indicated.
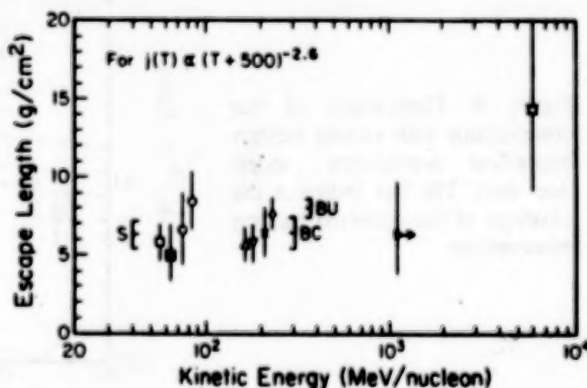
Table 1 - Mean Escape-Lengths (in g/cm²)

Source Spectrum	Spacecraft Observations (~ 70 MeV/nuc)	Balloon Observations (~ 200 MeV/nuc) w/o atm. corr.	Balloon Observations (~ 200 MeV/nuc) atm. corr. [1]
$(T+500)^{-2.6}$	6.3±0.9	8.0±0.6	6.4±1.1
$(T+200)^{-2.6}$	8.9±1.0	9.7±0.7	7.8±1.3

(1) Uncertainty includes systematic uncertainty in the magnitude of the atmospheric correction.

At low energies, the required λ_e ranges from ~6 to ~9 g/cm² (see Table 1), with the lower value appropriate to U≃500, a spectral form consistent with most studies of the propagation and solar modulation of Z≥3 nuclei (e.g., [15,14]). An escape length of 6 g/cm² agrees well with that derived from the B/C ratio at similar energies (see, e.g., [16,14]). We conclude that low-energy observations of ^{3}He/^{4}He are in excellent agreement with the propagation and modulation parameters derived for heavier nuclei.

The above conclusion agrees with most earlier studies of low-energy H and He isotopes that have included both propagation and solar modulation effects (e.g., [17,4,8]), but it is in marked *disagreement* with the recent interpretation of low-energy observations by J&M [9,10]. They suggested that balloon observations at ~100 to 300 MeV/nucleon were consistent with the $\lambda_e \simeq 15$ g/cm² escape-length required by their own measurement. After repeating their analysis in detail we conclude that J&M have significantly overestimated the pathlength required by the balloon data, as a result of a combination of factors, and that self-consistent interpretations of the low-energy data imply $\lambda_e(^4$He$) \leqslant 10$ g/cm². This conclusion is independent of the magnitude of the proposed atmospheric correction for the balloon data, but it is strengthened by the apparent need for this correction, and also by the spacecraft observations.

Measurements of Z≥3 nuclei imply a energy-dependent escape-length that decreases with energy above several GeV/nucleon. Figure 4 shows the expected ^{3}He/^{4}He ratio for the energy-dependent escape-length ($\lambda_{OP}(E)$) of Ormes and Protheroe [14], for two spectral forms. Both spectra can be seen to be consistent with the low-energy ^{3}He/^{4}He observations and inconsistent with the J&M measurement. Although the U=500 curve falls somewhat above the data, it should be pointed out that $\lambda_{OP}(E) \simeq 9$ g/cm² at several hundred MeV/nucleon, which is also greater than required by the B/C ratio. Thus the marginal agreement for U=500 is most likely the result of an inadequacy of the energy dependence of λ_{OP} at low energies.
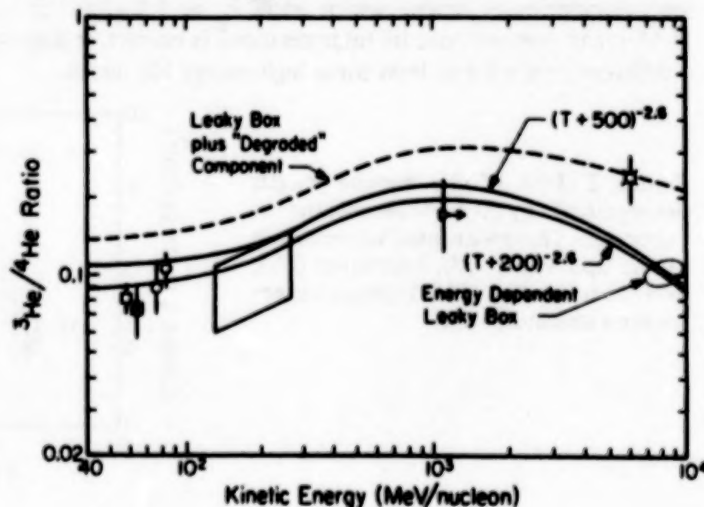
Figure 4: Comparison of the observations with various energy-dependent propagation models (see text). The box indicates the envelope of the corrected balloon observations.

Recent observations of an excess of antiprotons and positrons at high energies have led to several new cosmic ray origin and propagation models in which some nuclei have traversed a great deal of material. Such models also produce an excess of ^{2}H and ^{3}He. As an example, Figure 4 shows the predicted ^{3}He/^{4}He ratio for the model of Cowsik and Gaisser [18], in which a "degraded" component of cosmic rays originates in "thick" sources surrounded by ~50 g/cm^2 of material. While this model is consistent with the J&M observation, it exceeds the observed ^{3}He/^{4}He ratio at low energies. By relaxing the assumption that the "normal" and "thick" sources have the same energy spectra and composition, it might be possible to fit both the high energy data (including the antiproton data) and the low-energy ^{2}H and ^{3}He observations.

Appendix - Atmospheric secondaries are an important source of background for balloon-borne ^{2}H and ^{3}He observations. One such contribution, which arises from the breakup of atmospheric N and O nuclei, leads to steeply falling spectra of ^{2}H and ^{3}He that are most significant below ~100 MeV/nucleon (see, e.g., [19,20]). While this source *has* been taken into account in most previous studies, an additional source, due to the breakup of *primary* ^{4}He and heavier nuclei, has generally been ignored. Although we are not aware of appropriate cross section measurements for ^{4}He breaking up into ^{3}He in collisions with CNO, with ^{4}He + p cross sections [12] at ~100 to 300 MeV/nucleon ~0.5 ^{3}He and ~0.4 ^{2}H are produced per inelastic ^{4}He interaction. We might expect ^{4}He + CNO interactions to produce somewhat fewer ^{3}He and more ^{2}H than ^{4}He + p interactions [12], since CNO targets tend to fragment ^{4}He to a greater degree. As an estimate of the "fragmentation parameter" for producing ^{3}He from ^{4}He in interactions with CNO we take P_{43}~0.25±0.15, in which case a typical ^{3}He/^{4}He ratio of 0.1 at 0 g/cm^2 will increase by ~17% at 3 g/cm^2 due to this process. Using this estimate (see also [21]) we have re-corrected the balloon observations in Figure 2 to the top of the atmosphere. This presently uncertain correction might be measured with observations of ^{3}He/^{4}He vs. atmospheric depth.

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21. We also assume inelastic mean free paths of 45 and 50 g/cm^2 for ^{4}He and ^{3}He, respectively [8], and that the energy/nucleon and angle of the incident ^{4}He and outgoing ^{3}He are the same.

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Results of a Search for Deuterium
at 25-50 GV/c Using a Magnetic Spectrometer

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Abstract

A method is presented for separately identifying isotopes using a
Cherenkov detector and a magnet spectrometer. Simulations of the
method are given for separating deuterium from protons. The
simulations are compared with data gathered from the 1979 flight
of the New Mexico State University balloon-borne magnet
spectrometer.   The simulation and the data show the same general
characteristics lending credence to the technique. The data show
an apparent deuteron signal which is $(11 \pm 3)\%$ of the total sample
in the rigidity region 38.5-50 GV/c.   Until further background
analysis and subtraction is performed this should be regarded as
an upper limit to the deuteron/(deuteron+proton) ratio.

1. Introduction. Measurement of particle mass by combining
information about a particle's velocity and its momentum is a
concept usually introduced in lower division physics courses. We
employ a   variation on the technique wherein the quantities
measured are the light level in a Cherenkov detector and the
magnetic deflection (1/magnetic rigidity).   Cosmic ray Cherenkov
detectors and magnet spectrometers have limited capabilities at
present.   In this paper these limitations are explored using
monte-carlo simulations based on the characteristics of the NMSU
spectrometer. We then compare the expected performance with data
gathered in the most recent flight of the spectrometer.

2. Simulations. The basic approach used here to separate
isotopes is to plot the two measured quantities, light level (in
the Cherenkov detector) vs magnetic deflection. For a given
particle the light level should be consistent with zero at
deflections larger than the Cherenkov threshold (ie at rigidities
below the Cherenkov threshold).   At deflections less than the
Cherenkov threshold a small amount of light would be registered
and at progressively smaller deflections, the light level should
rise to a maximum which is determined by the characteristics of
the particular detector (and the charge of the particle).   The
relationship between deflection and light level can be derived
from the more classical representations (see eg (1)) by

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defining d_T as the deflection threshold and Nmax as the light level for a $\beta = 1$ (ie deflection = 0) particle. In this case we have:

$$\bar{N} = N_{max}(1 - (d_T/d)^2)$$ (1)

where $\bar{N}$ is the average number of photoelectrons
and d is the magnetic deflection.

The deflection thresholds for particles of different masses are related by:

$$(d_T)_1 / (d_T)_2 = m_2/m_1$$ (2)

For the flight in question, the Cherenkov detector had a proton Cherenkov threshold corresponding to a deflection of 0.43 c/GV (23 GV/c rigidity). Figure 1a shows light level vs deflection curves derived from equations 1 and 2 using a proton threshold of 0.23 GV. These curves neglect uncertainties in the light level and the deflection. Note that two types of particles (protons and deuterium) are shown. The two types have different Cherenkov rigidity thresholds and different light-level vs deflection curves owing to their different masses.
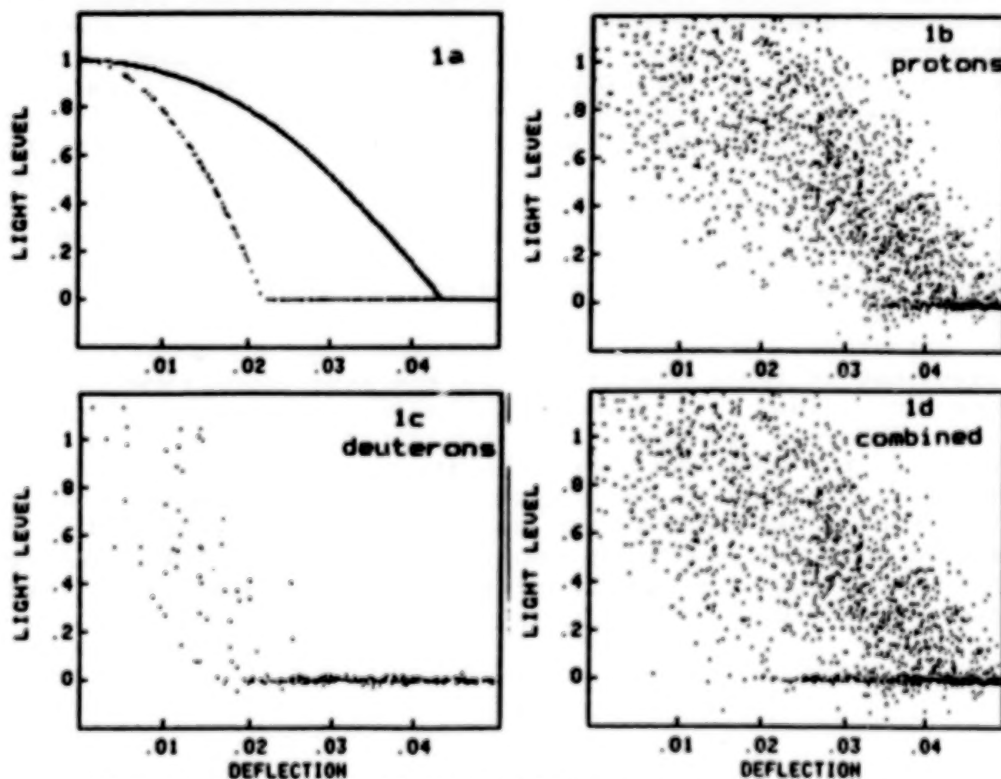
Figure 1. Simulation of Light Level vs Deflection

In order to assess the effects of finite deflection resolution and statistical fluctuations in the photoelectron count, we have repeated the calculation for Figure 1a with the addition of gaussian errors in the deflection and light level for each event. The deflection error distribution had a sigma of 0.029 c/GV (corresponding to an MDM of 350 GV/c), and the light level was varied by a gaussian whose sigma was sqrt(N). The maximum light level was taken to be 10 photoelectrons. A poisson distribution in light level would have been more correct but the difference is only noticeable at low light levels. Figure 1b shows the distribution for 3000 protons; Figure 1c shows the expected distribution for 300 deuterons, and Figure 1d shows the distribution for 3000 protons and 300 deuterons, combined. Note that the deuteron signal is still visible in Figure 1d. By comparing Figs. 1b, 1c and 1d we see that the best place to test for deuterons is at low light levels at deflections just to the right of the deuteron threshold. Note also that as one moves progressivly left of the deuteron threshold, the counts should diminish to zero.

3. Observations. Initial selection of events to be used in the deuterium hunt was similar to the selection of protons in the antiproton hunt reported elsewhere (2),(3). The quoted deflection resolution for this sample 0.08 c/GV corresponding to a maximum detectable rigidity of 125 GV/c. Studies of e- encountered during the flight showed that the maximum light level for the experiment (averaged over all trajectories) was about 7 photoelectrons. In order to obtain a data sample with a deflection resolution of 0.029 c/GV, only trajectories that traversed more than 5 KG-m of magnetic field were selected. Studies of the e- indicated that by eliminating trajectories that went near the mirror edges, and by using only events whose photons should have been centered within 14 cm of a phototube face, the average maximum light level could be raised to about 10 photoelectrons. About 15% of the protons reported in the antiproton papers (2),(3) survived these additional criteria. Figure 2 shows the light-level vs deflection points from the events selected. The similarity between Figure 2 and Figure 1d indicates that at least qualitatively the instrument response is as expected. The region where deuterons should be detectable does indeed have a few counts in it, and the region from zero deflection to the deuteron Cherenkov threshold appears to contain relatively few counts. The reader is cautioned however that a detailed background subtraction has not yet been performed. It is possible that the events at low light-level near the deuteron threshold are due to spillover from the protons near their Cherenkov threshold.
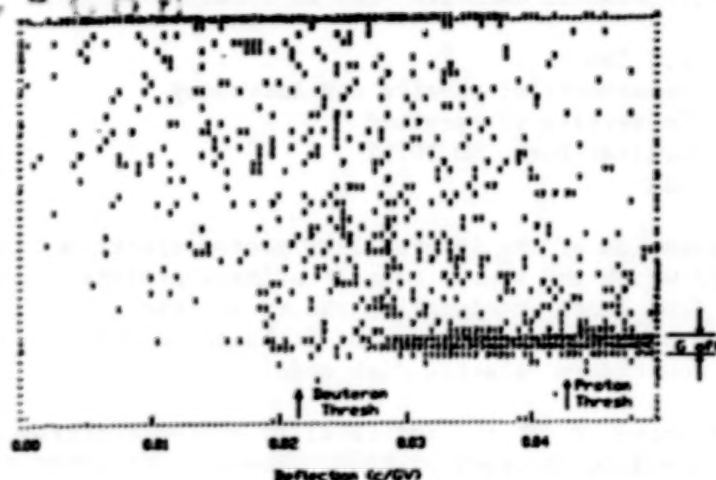
Figure 2.
Light Level vs
Deflection
(3115 events)

In order to estimate the deuteron content (upper limit for now) indicated by Figure 2, we have computed the ratio of G-off events to all events as a function of deflection. G-off events are defined as those whose light-level is within the limits shown on Figure 2. This ratio is shown in Figure 3. Note the apparent "shelf" in the deflection region 0.02-0.03 c/GV. The average value of the leftmost three intervals is (11 ± 3)%. This could be regarded as a measurement of the deuteron/(deuteron + proton) ratio except that a background subtraction has not been made. Thus the result must for now be regarded as an upper limit.
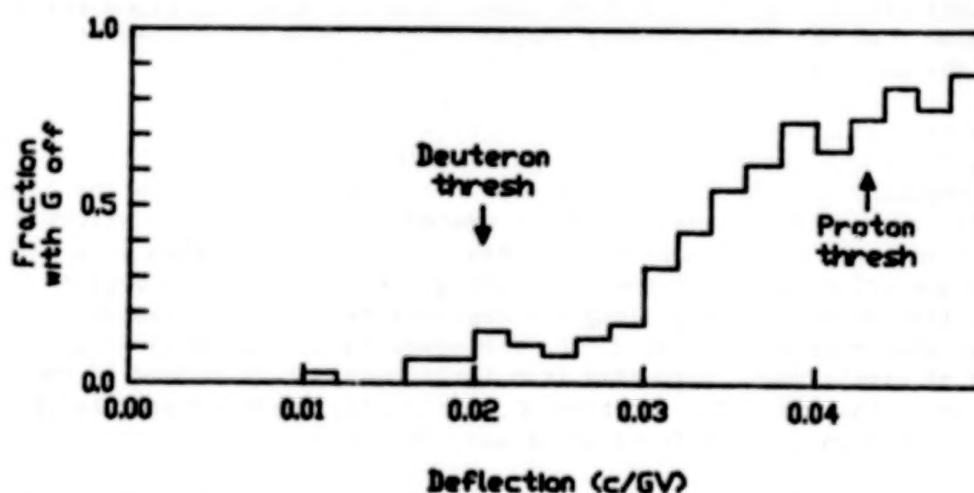
Figure 3. Fraction of G-off Events vs Deflection

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PARAMETRIZED ENERGY SPECTRUM OF COSMIC-RAY PROTONS WITH KINETIC ENERGIES DOWN TO 1 GeV

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A new estimation of the interstellar proton spectrum
is made in which the source term of primary protons
is taken from shock acceleration theory and the
cosmic-ray propagation calculation is based on our
proposed nonuniform galactic disk model.

It appers that above 10 GeV the interstellar proton spectrum can be
determined with an absolute accuracy of ±20%. However, at lower energies
the divergence among various spectral estimations is much more serious;
this is due to the existence of solar modulation. Thus one needs to
deduce the interstellar proton spectrum through his own demodulation
calculation. The deduced proton spectrum is obviously dependent upon
the model of solar modulation used.

Recently, an interesting attempt for deducing the interstellar
proton spectrum is reported(1), in which a source term of primary protons
suggested by shock acceleration theory is adopted and the cosmic-ray
propagation calculation is based on the leaky box model. Since from our
recent analysis of the high-energy electron spectrum(2) we are aware that
the dominant part of observed protons comes from the dence H_2 cloud region,
it is argued that the corresponding propagation calculation should be
based on the nonuniform galactic disk (NUGD) model(3).

Here we will present a brief introduction to the NUGD model.
According to it the observed cosmic rays contain two components: the
distant component and the local component. As shown in Fig. 1 by the
double-line arrows, the distant (left) component of cosmic rays, starting
from the cosmic-ray confinement volume above the H_2 cloud region (Box 2)
can reach the solar neighbourhood by escaping into the H_2 cloud region
(Box II), then by propagating along the magnetic tube (Box I) inside
which the solar system is located. On the other hand, the local (right)
component of cosmic rays originates from their confinement volume in the
solar vicinity (Box 1). The fraction, ϵ, of locally produced protons in
the observed proton flux is found to be only 5±1 %(2).

The main problem in extending the application range of the NUGD model
to the low energy range is caused by a lack of knowledge of the convection
velocity (V) of cosmic rays. Thus at low energies one is unable to
determine a precise shape of the cosmic-ray escape pathlength (λ_e) in
Box II or to estimate the cosmic-ray intensity variation along the
magnetic tube (Box I). Nevertheless, it is noted that if we limit
ourselves to interstellar protons with kinetic energy, $T_p \geqslant 1$ GeV, to a
great extent we can avoid the difficulties shown above. Actually, the
proton intensity in the H_2 cloud region (Box II) should be the same as in
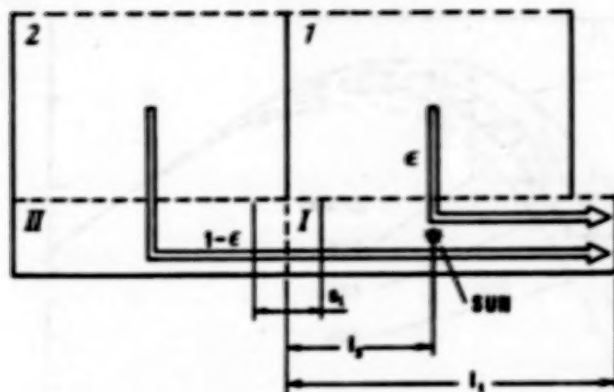
Fig. 1

Box 1 or Box 2, because it is found experimentally that there is a lack of any cosmic-ray gradient, at least in the inner Galaxy (see Ref. 4). Note that at any given rigidity (R) protons are the dominant component of cosmic rays. Hence we do not need to use the unknown parameter λ_{eII} to estimate the proton intensity in Box II (hereafter the subscripts 1, 2, I and II represent the quantities referred to Boxes 1, 2, I and II respectively).

Regarding the λ_e value in Box 1 or Box 2 we will use the empirical relationship(1) deduced from measured data on heavy nuclei. Furthermore, in Box I the pathlength (x_I) of cosmic rays to reach the solar neighbourhood has been estimated(2). It is noticeable that even if cosmic-ray particles lack any convection motion in Box I, protons with $T_p \geqslant 1$ GeV should have a value of x_I less than $0.3 \lambda_p^i$, where λ_p^i is the mean inelastic interaction length of interstellar protons, to reach the solar neighbourhood. As a result, the proton intensity variation along the magnetic tube should be insignificant, and we will only consider two extreme cases (V= 0 and V= 300 km/s) to estimate the range of variation of the proton spectrum.

In order to deduce the proton intensity N_{p12} in Box 1 or Box 2 we need to solve the continuity equation of primary protons,

$$N_{p12}\left(\frac{1}{\lambda_{e12}} + \frac{1}{\lambda_p^i}\right) = q_{p12} + \int_{T_p}^{\infty} \frac{1}{\lambda_p^i} \frac{dN_p(T_p',T_p')}{dT_p} {}^p N_{p12}(T_p')dT_p', \quad (1)$$

where q_p is the source term of primary protons and $dN_p/dT_p = 1/T_p'$ is the energy distribution of protons after their inelastic interactions. From shock acceleration theory we have

$$q_{p12} = k_{0p} \, p^{-(2+\eta)}/\beta_p c, \quad (2)$$

where p is the proton momentum, k_{0p} is a constant, $\eta = 0.05$ and $\beta_p c$ is the proton velocity. Since at low energies the power law approximation of N_{p12} and the constant approximation of λ_p^i cannot be used, an iteration procedure is used to obtain the numerical solution of N_{p12}.
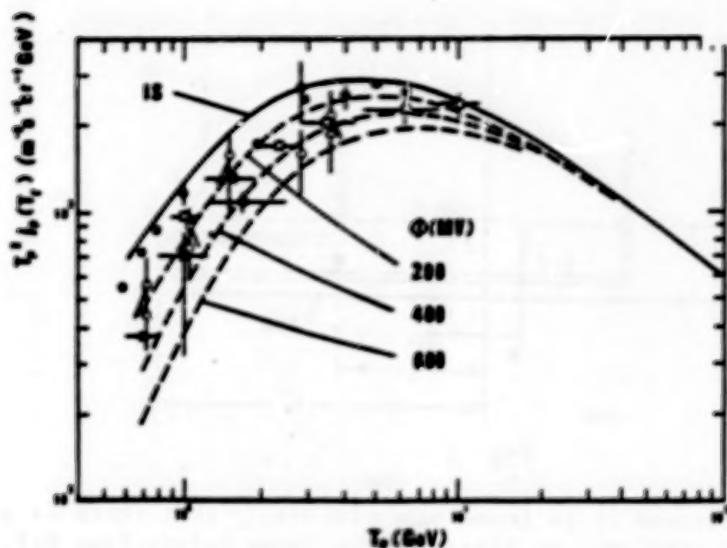
Fig. 2

Further, the propagation of interstellar protons along the magnetic tube (Box 1) can be described by using a slab model,

$$\frac{dN_{pI}(T_p, x_I)}{dx_I} = -\frac{N_{pI}(T_p, x_I)}{\lambda_p^i} + \int_{T_p}^{\infty} \frac{1}{\lambda_p^i} \frac{dN_p(T_p, T'_p)}{dT_p} N_{pI}(T'_p, x_I) dT'_p , \qquad (3)$$

where the initial value of N_{pI} should be N_{pII} after any possibly adiabatic deceleration in the assumed boundary layer s_1 (see Fig. 1)(3). At lower energies we also have

$$x_I = 4x_{I0} R^{-0.7} (1+(1+2q_s)^{1/2})^{-2} , \qquad (4)$$

where x_{I0} is a constant, $q_s = V1_s/K_s$ and K_s is the diffusion coefficient of cosmic rays. Similarly, a numerical method is developed to obtain the solution of Eq. (3) in the solar neighbourhood, N_{ps}. Thus the proton intensity predicted for the NUGD model should be

$$N_{pp} = (1-\varepsilon) N_{ps} + \varepsilon N_{pl2} , \qquad (5)$$

where $\varepsilon = 5\pm1$ % as deduced from Ref. (2).

It is found that the effect of taking various values of V is negligible, and the resultant cosmic-ray proton spectrum in the solar neighbourhood can be parametrised as

$$j_{pp}(T_p(GeV)) = \frac{2 \cdot 10^4 T_p^{-2.75}}{1 + C_1 T_p^{-1.58}} , \qquad (m^{-2}s^{-1}sr^{-1}GeV^{-1}) \qquad (6)$$

where $\qquad C_1 = 15.0 - 6.05\ln T_p + 2.84\ln^2 T_p + 0.169\ln^3 T_p .$ $\qquad$ (7)

The predicted j_{pp} spectrum is not only in accordance with the existing proton data at $T_p \gtrsim 10$ GeV, but also is consistent with the low-energy proton data measured in the period of solar minimum(5) (see Fig.2).

T_p (Gev)
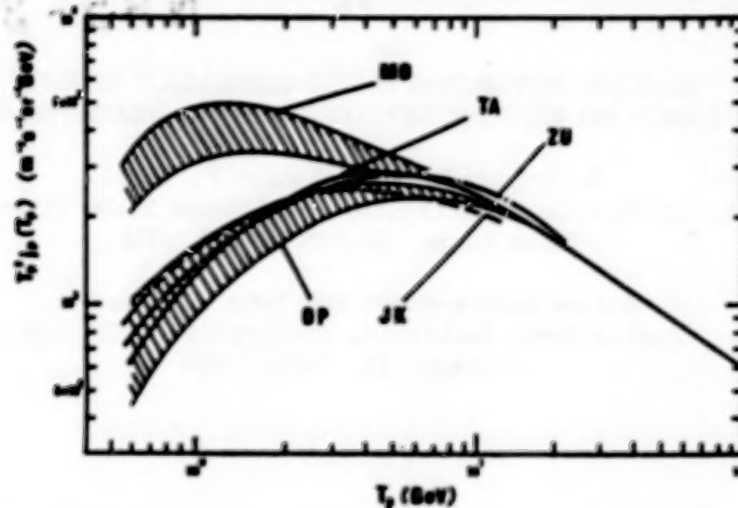
Fig. 3

The modulated spectra in Fig. 2 are obtained from our predicted j_{pp} spectrum by using the force field approximation. It appears that the measured data are consistent with our modulated spectrum with $\phi = 200 \pm 200$ MV, where ϕ is the mean energy loss per nucleon in the heliosphere for cosmic-ray nuclei(6).

Finally, in Fig.3 our deduced interstellar proton spectrum (TA) is compared with the results of other authors (OP(1),MO(7),ZU(8) and JK(9)). It is noticeable that our proton speccrum is close to the demodulated spectra recently suggested in Refs. (8) and (9), indicating the general reasonableness of the demodulation processes used in these works. In conclusion, the parametrized expression of our deduced interstellar proton specrum should be useful in various cosmic-ray calculations, in particular in the estimation of the production rates of cosmic-ray secondary particles in interstellar space.

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GALACTIC PROPAGATION MODELS CONSISTENT WITH THE
COSMIC RAY LIFETIME DERIVED FROM ^{10}Be MEASUREMENTS

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ABSTRACT

Using a propagation calculation with energy dependent
parameters, including the depletion of short pathlengths,
and incorporating experimental nuclear excitation functions,
the variation of the ^{10}Be/^{9}Be ratio with the matter
densities in two nested confinement regions is investigated.
It is shown that there is no unique correspondence between a
^{10}Be/^{9}Be measurement at low energy and the density of matter
in the galaxy. ^{10}Be/^{9}Be measurements at both low and high
energy are needed to fully specify the matter densities.

1. Introduction   In recent years considerable progress has been made
in determining the energy dependence of the pathlength distribution
(PLD) for cosmic ray propagation at low energies in the interstellar
medium (Garcia-Munoz et al., 1985). However, previous analyses of
radioactive cosmic ray isotopes have been done in the context of the
simple "leaky box" model, which does not explain, simultaneously, the
energy dependence of the measurements of both light and heavy secondary
to primary elements (such as B/C and V/Fe or Sc/Fe). In this report, we
present results of propagation calculations for ^{10}Be/^{9}Be using
experimental nuclear excitation functions and energy dependent
parameters in the PLD which give results in agreement with both B/C and
sub-Fe/Fe ratios from 100 MeV/n to 30 GeV/n.

2. The Propagation Calculations   The propagation code employs the
weighted slab technique to calculate the abundances of 96 stable, long-
lived or electron capture isotopes from ^{4}He to ^{64}Ni. Radioactive
decay (β^+, β^-, electron capture) is treated explicitly; the effects of
ionization energy loss are included; and energy dependent total
inelastic cross sections, based upon compiled experimental data, are
employed. The partial fragmentation cross sections are based upon semi-
empirical formulae of Silberberg and Tsao (1973), modified using
available experimental data. Cosmic ray source abundances are from
Garcia-Munoz and Simpson (1979), and the ratio of H to He in the
interstellar medium is from Cameron (1981). The majority of the cosmic
ray data used here were collected during the last period of minimum
solar modulation (1974-1979), and the calculations include modulation
with an adiabatic deceleration parameter ϕ = 490 MV (Evenson et al.,
1984).

The propagation
code was run in two
modes: single and double
runs. In a single run,
the abundances of all
species were calculated
for a series of slabs
and then weighted by a
single, energy dependent
pathlength probability
distribution. Such a
PLD is illustrated in
Fig. 1 where the inset
(B) shows the overall

Fig. 1: The energy dependent DE PLD.

shape of the Double Exponential (DE) form, composed of two exponentials
with means X_1 and X_2, where X_2 represents the depeletion of short
pathlengths (Garcia-Munoz et al., 1984). The energy dependences of X_1
and X_2, shown on part A along with the mean pathlength <X>, are
determined by fitting the B/C and sub-Fe/Fe data over the energy
range 0.1 - 30 GeV/nucleon (Guzik and Wefel, 1984). The DE PLD is
qualitatively similar to earlier models (Garcia-Munoz and Simpson,
1970), e.g. the PLD in the "nested leaky-box" model (Cowsik and Wilson,
1975), but is quantitatively different since our DE PLD includes energy
dependent parameters.
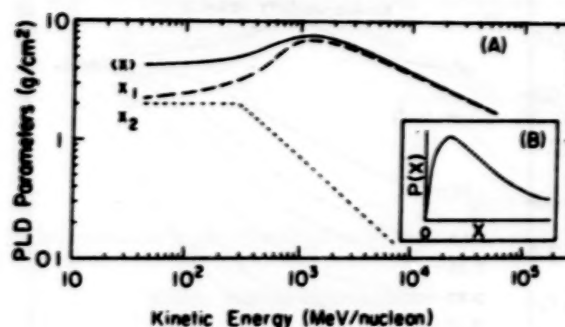
Fig. 2 shows a comparison of the calculated $^{10}Be/^9Be$ ratio for
different PLD's, for a constant density of 0.5 atoms/cm^3. The dashed
line is for a simple energy independent exponential which is
characteristic of the "leaky box" model. Note that when energy
dependence of the mean of the PLD is included (lower solid line) the
shape of the predicted $^{10}Be/^9Be$ is modified. However, neither of these
PLD's fit both the B/C and sub-Fe/Fe ratios. Such a fit requires an
energy dependent depletion of short pathlengths (a truncated PLD, see
Garcia-Munoz et al., 1984) and results for two types of truncation
(yielding essentially identical
results) are shown on Fig. 2
(upper solid and dot-dashed
curves). Note that above
several GeV/nucleon the curves
converge, as expected, since at
higher energies the truncation
becomes negligable (c.f. X_2 on
Fig. 1).

In analogy with the "nested
leaky box" model, the two
components of the energy dependent
DE PLD can be associated with
confinement in an inner region of
density ρ_{IN} (i.e. around the
sources) nested within an outer
region of density ρ_{OUT} (i.e. the
Galaxy) (Guzik and Wefel, 1984).
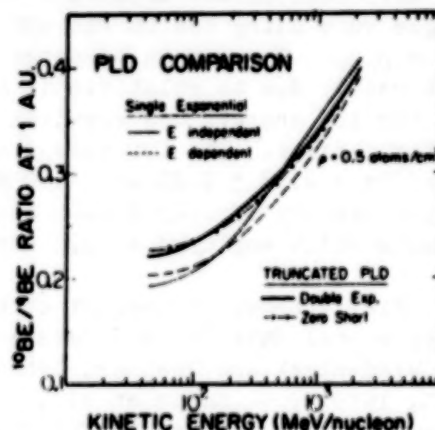
Fig. 2: $^{10}Be/^9Be$ results for
different PLD's.
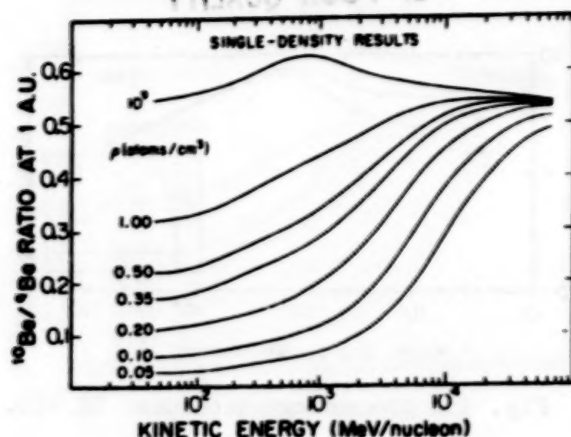
Fig. 3: ^{10}Be/^{9}Be ratio as a
function of density.

Double runs were used to study this
configuration of confinement regions.
In the first step, the propagation code
is run with an exponential PLD whose
mean follows the curve given by X_2 on
Fig. 1. For this step the matter
density has the value ρ_{IN}.   Next, the
results of step 1 are used as the
source for a second calcualtion (with
matter density ρ_{OUT}) whose PLD mean
follows the X_1 curve on Fig. 1.   This
two step method allows us to treat
separately the densities in the inner
and outer regions, which, physically,
could be quite different.

KINETIC ENERGY (MeV/nucleon)

3. Results   Figure 3 shows results
for different matter densities from
single runs using the DE PLD with
$\rho_{IN} = \rho_{OUT}$. The curves converge at
high energy due to relativistic effects,
and for low energy, the survival of ^{10}Be is directly dependent upon the
matter density. The low energy satellite experiments give a mean value
^{10}Be/^{9}Be = 0.13 ± 0.03 at ~100 MeV/n which implies from Fig. 3, a
matter density of 0.23 ± 0.06 atoms/cm^3, consistent with previous
results which employed single density analysis.
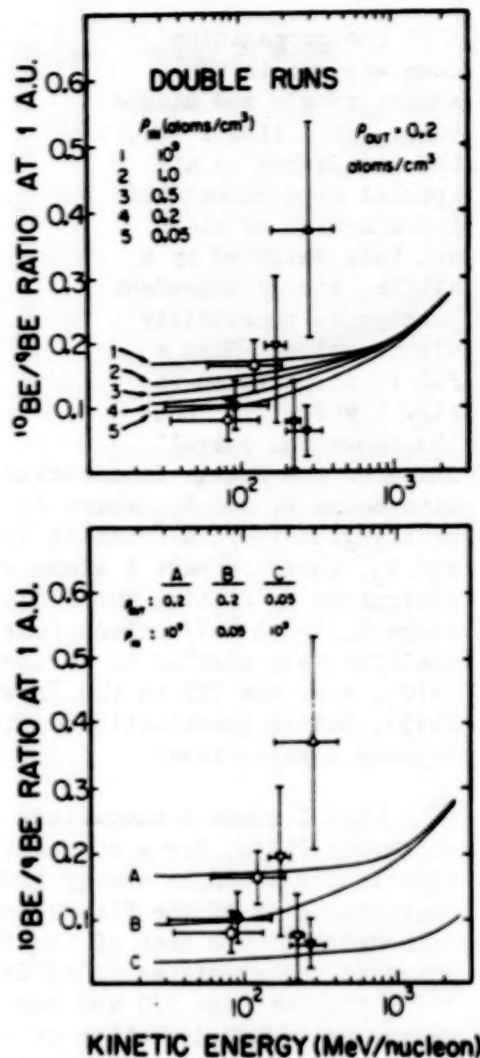
Fig. 4:   Results of the two-
step analysis compared to
experimental data.

Fig. 4 shows the result of the two-step calculations compared to
experimental data (o, • - Garcia-Munoz et al., 1977, 1981;
□ - Wiedenbeck and Greiner, 1980; ∇ - Webber et al., 1977; ▼ -Webber and
Kish, 1979; Δ - Hagen et al., 1977). The top panel shows the
calculated ^{10}Be/^{9}Be ratio for fixed ρ_{OUT} with ρ_{IN} allowed to vary from
0.05 to 10^9 atom/cm^3. Different values for ρ_{IN} spread the predicted
^{10}Be/^{9}Be ratio at low energy by about a factor of two. The curves
converge above 1 GeV/n since the effect of the inner region decreases
with increasing energy. In this model a measurement of the ^{10}Be/^{9}Be

ratio does <u>not</u> uniquely determine the density in the confinement region.

The measured $^{10}Be/^9Be$ ratio at low energy can provide bounds on the density in the outer region. This is illustrated in the lower panel of Fig. 4 where curves A and B show the total spread in the predicted ratio for ρ_{OUT} = 0.2 atoms/cm^3. Assuming a large value for ρ_{IN} allows a smaller value of ρ_{OUT} to be used to reproduce a given value of the $^{10}Be/^9Be$ ratio, as shown by curve C which forms a lower bound to the experimental data. Conversely, assuming a minimum value for ρ_{IN}, a value of ρ_{OUT} = 0.5 atom/cm^3 give an upper limit to the low energy data. Thus, the available measurements constrain ρ_{OUT} to the range 0.05 - 0.50 atoms/cm^3, below the average density of ~1 atom/cm^3 for the galactic disk and above the density of 0.01 atoms/cm^3 of a galactic halo.

4. <u>Conclusions</u>   The cosmic ray PLD, including an energy dependent depletion of short pathlengths, can be represented as two "nested" confinement regions having different matter densities. The available $^{10}Be/^9Be$ measurements do not uniquely determine the density in the outer region, but they do limit the allowed values to a range of 0.05 and 0.50 atoms/cm^3. $^{10}Be/^9Be$ data at high energy (currently unavailable) combined with existing measurements at low energy can determine the matter density in <u>both</u> volumes.

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IMPLICATIONS OF NEW MEASUREMENTS OF $^{16}O + p + ^{12,13}C, ^{14,15}N$ FOR THE ABUNDANCES OF C, N ISOTOPES AT THE COSMIC RAY SOURCE

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ABSTRACT

The fragmentation of a 225 MeV/n ^{16}O beam has been investigated at the Bevalac. Preliminary cross sections for mass = 13,14,15 fragments are used to constrain the nuclear excitation functions employed in galactic propagation calculations. Comparison to cosmic ray isotopic data at low energies shows that in the cosmic ray source $^{13}C/C \leq 2\%$ and $^{14}N/O = 3 - 6\%$. No source abundance of ^{15}N is required with the current experimental results.

1. __Introduction:__   The interpretation of cosmic ray measurements in terms of the source abundances and the propagation conditions requires accurate nuclear physics parameters. The current cosmic ray data is, in many cases, better than our ability to interpret it. In particular, the interpretation of the isotopic abundances of carbon and nitrogen, as a function of energy, requires nuclear excitation functions for masses 13, 14 and 15, and we report here preliminary results from an experiment designed to study the fragmentation of ^{16}O at intermediate energy.

2. __The Bevalac Experiment:__   Figure 1 shows the experimental arrangement at the LBL Bevalac. The ^{16}O beam, incident from the right, passed through monitors S1 and S2, focussing and bending magnets, and steering scintillators upstream of the target, located in a vacuum tank. Fragments from interactions in the targets (~ 1 g/cm^2 C and CH$_2$) were measured ~ 7 meters downstream in the cave with a solid state detector telescope (Scope) which was moveable in order to study the angular distributions of the fragments. The Scope consisted of three x-y

LBL Bevoloc - Beam 40 - Experiment 683H
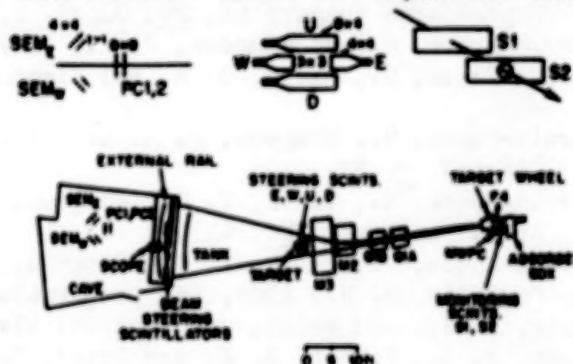
Fig. 1: Experimental Configuration

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planes of position-sensitive detectors and a stack of 30 Li-drifted detectors. The ΔE-E technique was employed to measure the mass of each particle stopping in the scope.

Six angular positions from 0° to 2.75° were studied and the cross sections were obtained by integrating under the normalized angular distributions after correction for background, beam effects, and interactions in the detector stack. Hydrogen target cross sections were obtained by CH_2-C subtraction. The isotopes of B, C, N and O have been analyzed to date, and here we focus on the A= 13, 14, 15 isobars for which the cross sections in hydrogen are:

	This Work	Predicted
A = 13:	24 ± 2 mb	(23.9 mb)
A = 14:	40 ± 4 mb	(50.4 mb)
^{15}N:	27 ± 2 mb	(24.6 mb)
^{15}O:	50 ± 20 mb	(34.2 mb)

compared to the predictions of the semiempirical equations (Silberberg and Tsao, 1973). For $^{14,15}O$, significant measurements were obtained only at large angles due to a beam veto circuit used at small angles to reduce the number of ^{16}O nuclei analyzed. The $^{14,15}O$ measurements were extrapolated to 0° thereby accounting for the large uncertainty. For the astrophysical interpretation, we prefer to rely on the semiempirical values for $^{14,15}O$, until additional experimental data can be analyzed.

Figure 2 shows the results of this experiment compared to previous data and to various excitation functions: solid curves -- semiempirical formulae; dashed curves -- scaled from ^{12}C measurements; dot-dash curves -- "limiting" cases (Guzik, 1981; Guzik and Wefel, 1984a). For A = 15, the predicted excitation functions are similar, and the present results are in agreement with semiempirical or scaled predictions. For A = 14, however, the present results are closest to the scaled curve, while for mass 13 the semiempirical curve is indicated. In all cases the
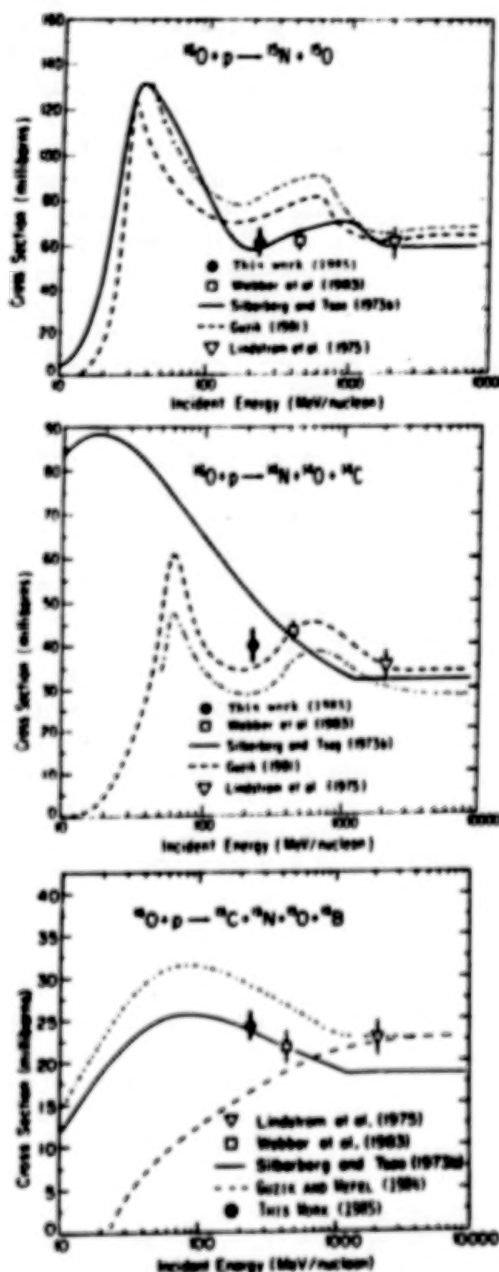
Fig. 2: Excitation Functions for A = 13,14,15 Isobars

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measurements do not support the "limiting" curves. It should be noted
here that the present results are still _preliminary_ and that
measurements at additional energies will be necessary to fully determine
the energy dependence of these excitation functions.

3. The Astrophysical Interpretation:

Isotopic measurements of
nitrogen are presently available at both low and high energy. In the
latter case, the results at the cosmic ray source give $(^{14}N/O)_S$ =
5 - 10% with no ^{15}N required (Goret
et al., 1983; see also review in
Guzik, 1981). At low energy (~ 150
MeV/n), there are several reported
isotopic measurements (Guzik, 1981;
Wiedenbeck et al., 1979; Mewaldt et
al., 1981) whose interpretation
depends upon the adopted nuclear
excitation functions. Isotopic
measurements of $^{13}C/C$ (Mewaldt et
al., 1981; Wiedenbeck et al., 1981)
provide a $(^{13}C/C)_S$ ratio which can
be compared to $^{13}C/C$ measured in
different regions of the galaxy
(Wannier, 1980).

The three excitation functions
shown on Fig. 2 have been
incorporated into cosmic ray
propagation calculations using a
pathlength distribution with energy
dependent parameters, including the
depletion of short pathlengths which
reproduces the measured B/C and sub-
Fe/Fe ratios over the full energy
range 0.1 - 50 GeV/n (for details
see Garcia-Munoz et al., 1984; Guzik
et al., 1985; Guzik and Wefel,
1984a;b). The results are shown on
Figures 3 and 4 where the curves
correspond to the excitation
functions shown on Fig. 2.

The weighted mean of the low
energy nitrogen data points (shown
individually for comparison) is
indicated as the solid box in the
center of Fig. 3, and the dashed
lines labeled $(^{14}N/O)_S$ give the
locus of points for different source
abundances (no ^{15}N at the source).
For the calculations to reproduce
both the elemental _and_ isotopic
ratios, at the 1σ level, excitation
functions between the scaled and
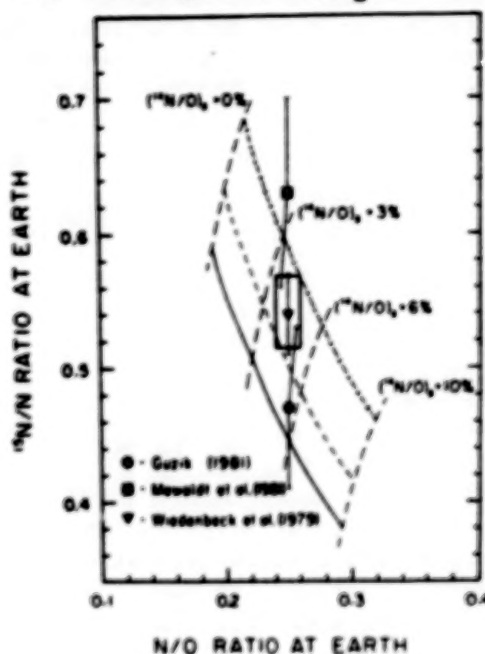
Fig. 3: Results for Nitrogen
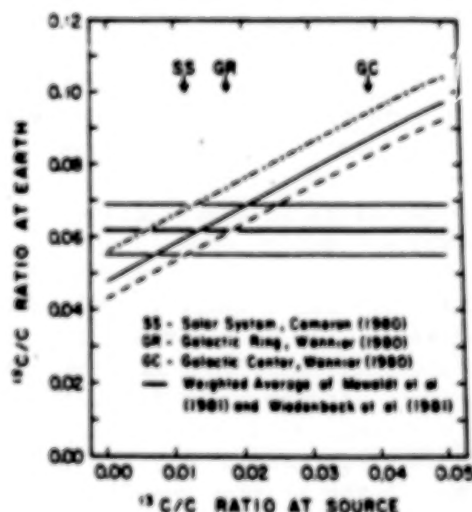
Fig. 4: Results for Carbon

limiting cases are required. Our preliminary cross section
measurements, however, indicate a more complicated excitation function
falling between the solid and the dashed curves. The results of a
propagation calculation using such an excitation function is
inconsistent with the 1σ data box on Fig. 3, but in agreement at
the 2σ level for $(^{14}N/O)_S = 3 - 6\%$.

Fig. 4 shows the results for $^{13}C/C$. The center horizontal line is
the measured ratio with the uncertainty indicated by the lighter
horizontal lines. The solid excitation function is favored on Fig. 2
which implies $(^{13}C/C)_S = 1.4 \pm 0.6\%$, in agreement with material found in
the solar system but below the ratio observed for matter at the galactic
center.

4. Conclusions: Using new cross section data, measured at the
Bevalac, for the fragmentation of ^{16}O at intermediate energies, galactic
propagation calculations can reproduce the measured $^{13}C/C$ data with a
source component $(^{13}C/C)_S = 1.4 \pm 0.6\%$, a value below that observed in
the galactic center. The calculated results for nitrogen fall below the
average $^{15}N/N$ and N/O ratios but are consistent with the data at the 2σ
level for $(^{14}N/O)_S = 3 - 6\%$ and no ^{15}N in the cosmic ray source.
Additional nuclear physics measurements are needed to fully specify the
excitation functions and to explain, completely, the existing cosmic ray
data.

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THE ISOTOPIC COMPOSITION OF COSMIC RAY CHLORINE

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ABSTRACT

The isotopic composition of galactic cosmic ray chlorine
(E≈225 MeV/amu) has been studied using the high energy
cosmic ray experiment on the ISEE-3 spacecraft. The abun-
dances of ^{35}Cl and ^{37}Cl are found to be consistent with
the secondary production expected from a propagation model
developed to account for both light and sub-iron second-
aries. An upper limit on the abundance of the radioactive
isotope ^{36}Cl (halflife = 0.3 Myr) is used to set a lower
limit on the confinement time of cosmic rays of ~1 Myr.

1. Introduction. Studies of the abundances of secondary cosmic ray nuc-
lides at low energies (<500 MeV/amu) have shown that no single exponen-
tial distribution of pathlengths is adequate for the simultaneous inter-
pretation of both the light secondaries, Li, Be, and B, and the sub-iron
secondaries, Sc through Mn (see [1], and references therein.) As a
consequence, more elaborate models involving pathlength distributions
which are exponential for long pathlenghts, but which are deficient in
short pathlengths (<1-2 g/cm^2), have been developed [1]. The necessity
of introducing a second parameter (the amount of truncation) in order to
explain the abundances of two groups of secondary nuclides raises the
question of whether the propagation model is generally applicable or
simply an empirical fit with enough free parameters to permit agreement
with a relatively small body of data. This question is of considerable
practical importance since such propagation models are used to calculate
the secondary corrections needed to derive cosmic ray source abundances
from the observed abundances of nuclides of intermediate mass, including
the isotopes of neon, magnesium, and silicon, which are found to differ
significantly from solar system composition. If the propagation model
used did not accurately predict the secondary production of species of
mass intermediate between the light elements and the sub-iron elements,
sizeable errors in the derived source composition would result.

It is important to directly check the adequacy of accepted propaga-
tion models by testing their predictions of abundances of intermediate
mass secondary nuclides. However, few elements between Z=10 and Z=20
are clearly dominated by secondaries. Observations of the elemental
abundance of cosmic ray chlorine (Z=17) suggest that the isotopes ^{35}Cl
and ^{37}Cl may both be dominantly secondary, but direct measurements of
the isotopic composition of chlorine are needed to check whether this is
indeed the case.

In addition, the radioactive isotope ^{36}Cl (halflife = 0.3 Myr) is
one of the relatively small number of nuclides with Z ≤ 28 which beta
decay on a time scale suitable for studying the confinement time distri-
bution of cosmic rays. Since its halflife is shorter than that of the
other beta-active nuclides which have previously been investigated (^{10}Be

1.6 Myr; ^{26}Al, 0.87 Myr), it is useful for investigating the density of the matter encountered by cosmic rays during the final few percent of the time required for transport to the vicinity of the Earth.

2. Observations. We have investigated the isotopic composition of ga-lactic cosmic ray chlorine using data from the high energy cosmic ray experiment on the ISEE-3 spacecraft. These data, collected between August 1978 and April 1981, cover an energy interval from 140 to 360 MeV/amu. The instrument consisted of a silicon solid state detector telescope used to measure energy losses and total energy and a gas pro-portional drift chamber used to measure cosmic ray particle trajector-ies. The mass uncertainty is dominated by trajectory errors, and there-fore increases rapidly with the angle of the particle's incidence, measured from the normal to the detector surfaces. In previous studies of the isotopic composition of elements with Z<16 it was possible to restrict the analysis to events with incidence angles less than some maximum chosen to permit nearly complete separation of the individual mass peaks while retaining reasonable statistical accuracy. For 16<Z<26 however, the combination of poorer mass resolution (which is approxi-mately proportional to mass) and small natural abundances does not per-mit the selection of a fully resolved data set. Figure 1 shows the chlorine mass histogram obtained by utilizing data with incidence angles of 20° or less. Peaks corresponding to masses of 35 and 37 are evident, while ^{36}Cl is significantly less abundant and is not resolved from the other isotopes.
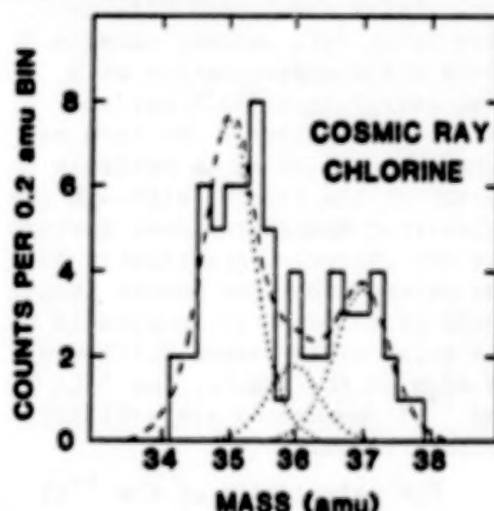
Figure 1. Observed chlorine mass histogram is shown together with the fitted mass distribution (dashed curve) and the three iso-tope peaks of which it is com-posed (dotted curves.)

Quantitative evaluation of the isotopic abundances (especially of ^{36}Cl) requires a detailed under-standing of the instrument's re-sponse to a mono-isotopic particle population. In order to obtain such an understanding, we have stu-died the dependence of mass resolu-tion on incidence angle ($\theta<20°$) for a number of abundant nuclides which are resonably well resolved from adjacent isotopes. The angular de-pendence is well fit by

$$\sigma_M = \sqrt{(a^2 + b^2 \cdot \sin^2 2\theta)}.$$

This form, with b∝M, is expected as a result of the fact that the mass resolution is dominated by trajec-tory uncertainties. The dependence of the coefficients a and b on the mass (or, equivalently, the charge) of the nuclide was studied by fit-ting this form for stable nuclides with mass numbers between 6 and 34, and for ^{45}Sc and ^{56}Fe. These coef-ficients were found to depend smoothly on mass over the entire range studied, and the b coefficient was proportional to mass, as expected.

The abundances of the three chlorine isotopes were obtained using a

maximum likelihood fit to the observed distribution of calculated masses, assuming the above functional dependence of mass resolution on incidence angle. The values of a and b obtained for chlorine agree, within errors, with the trend found for the other nuclides studied. The fitted mass distribution, together with the three isotope peaks of which it is composed, is shown superimposed on the observations in Figure 1. The derived isotope fractions, when combined with our observation of the element ratio Cl/S = 0.20 ± 0.02, yields the following near-Earth abundance ratios: ^{35}Cl/S = 0.116 ± 0.024, ^{36}Cl/S < 0.048, and ^{37}Cl/S = 0.058 ± 0.016. The errors shown are one standard deviation, and the ^{36}Cl upper limit is at the 84% confidence level. The element sulfur was chosen for the normalization since it is the nearest dominantly primary element to chlorine.
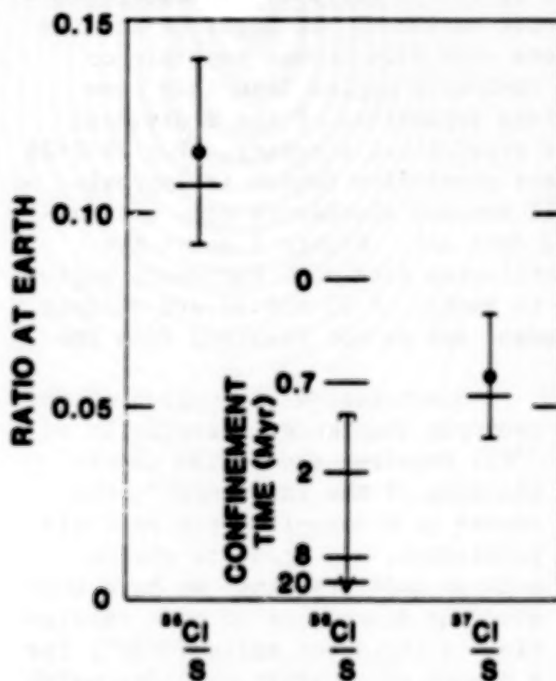
Figure 2. Observed chlorine isotope abundances (relative to the elemental sulfur abundance) are compared with the results of a propagation calculation (horizontal lines.) For ^{36}Cl the calculation depends on the cosmic ray confinement time.

3. Discussion. Figure 2 compares the observed abundance ratios with the predictions of a propagation model which is consistent with both light and sub-iron secondary element abundances (specifically, the ratios B/C and Sc+V/Fe) in low energy (~100-300 MeV/amu) cosmic rays. This model employs a nested leaky box with mean pathlengths of 1.5 and 3.0 g/cm^2 (with H:He=10:1) and standard cross section formulae. Solar modulation effects were taken into account using a force field approximation with mean energy loss Φ=325 MeV/amu (for A=2Z nuclides.) We have assumed that chlorine is entirely absent at the source, although the calculated abundances near Earth are not changed significantly if one assumes that the source abundance of chlorine is comparable to its solar system value (Cl/S=0.01). As seen in the figure, the ^{35}Cl and ^{37}Cl abundances are well fit by this model.

The calculation of the ^{36}Cl abundance at Earth depends on the assumed cosmic ray confinement time (or, equivalently, the assumed density of interstellar gas) since this parameter determines the fraction of the ^{36}Cl which decays between the time it is produced by spallation and the time it is observed at Earth. As previously pointed out [3], the ^{36}Cl abundance in the absence of beta decay is a sizeable fraction of the chlorine element abundance, so this isotope is useful for studying the cosmic ray confinement time in spite of the fact that its halflife is significantly shorter than that time (as determined from ^{10}Be), $T_{\frac{1}{2}}/\tau_{esc} \approx 0.04$.

Figure 2 includes calculated values of the ^{36}Cl/S ratio for various

values of the cosmic ray confinement time. Our lower limit on the near-Earth abundance of ^{36}Cl implies a cosmic ray confinement time greater than ~1 Myr. This limit is consistent with the confinement time values we previously reported based on the abundances of ^{10}Be [4] (8.4 [+4.0, -2.4] Myr), and ^{26}Al [5] (9 [+20, -6.5] Myr.)

The limited statistics and resolution in the present observations of ^{36}Cl do not allow a very stringent test of the homogeneity of the matter in the cosmic ray confinement volume. However, the consistency of both the interstellar pathlength distribution and the confinement time deduced from the observed chlorine isotopic abundances with those previously obtained from other stable and unstable secondary nuclide abundances indicate that no major differences exist in the confinement of different elements, at least in the range $3 \lesssim Z \lesssim 26$.

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COSMIC RAY ISOTOPE MEASUREMENTS WITH A NEW
CERENKOV X TOTAL ENERGY TELESCOPE

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1. Introduction and Experimental Data. In this paper we report measurements of the isotopic composition of cosmic ray nuclei with $Z = 7-20$. These measurements were made with a new version of a Cerenkov x total E telescope. This telescope and the details of the balloon flight are described in paper OG 4.1-5. Path length and uniformity corrections are made to all counters to a RMS level $< 1\%$. Since the Cerenkov counter is crucial to mass measurements using the C x E technique - special care was taken to optimize the resolution of the 2.4 cm thick Pilot 425 Cerenkov counter. This counter exhibited a $\beta = 1$ muon equivalent LED resolution of 24%, corresponding to a total of 90 p.e. collected at the 1st dynodes of the photomultiplier tubes.

Events to be analyzed using the C x E mass analysis technique are first selected according to charge by a two dimensional method using both dE/dx xE and dE/dx xC matrices. Three separate dE/dx measurements are utilized. Charge overlap is neglible. Mass histograms are constructed from C x E matrices for each charge as illustrated in Figure 1 for Oxygen nuclei. Mass histograms for N, O, Ne and Mg nuclei are shown in Figure 2, and for Al, Si, S, Ar and Ca nuclei in Figure 3. The mass resolution is $\sigma \sim 0.23$ AMU for ^{16}O and 0.27 AMU for ^{28}Si.

The data from the 30 hour balloon flight is summarized in Table I. Column 1 gives the energy interval for mass analysis. The upper limit is taken to be $C/C_{max} = 0.45$ for Mg and heavier nuclei. Column 2 gives the number of events observed. Errors are shown only for isotopes where significant mass overlap occurs - all other errors are taken to be statistical. Column 3 shows the charge fraction for each isotope corrected to equal energy/nucleon intervals. And finally Column 4 shows this charge fraction corrected to the top of the atmosphere.

2. Interpretation of the Data. The basic goal of this experiment is to compare the observed isotopic ratios with those expected after interstellar propagation in order to derive the cosmic ray source abundance ratios. The secondary abundances produced during propagation are calculated using new cross sections measured by our group at the BEVALAC (Webber et al., paper OG 7.2-2). The propagation program utilizes a simple exponential path length distribution in hydrogen with a mean path length $\lambda_e = 23.0 \ \beta \ P^{-0.6}$ g/cm^2 above 5.5GV and $\lambda_e = 8.33 \ \beta$ below 5.5GV. The solar modulation parameter $\Phi = 600$ MV. At an interstellar energy ~ 800 MeV/nuc appropriate to these measurements, $\lambda_e \sim 6.8$ g/cm^2.

The extrapolation to the source for selected isotope ratios is shown in Table II. Also shown for comparison are previously measured isotope ratios (at a slightly lower energy) from a summary by Wiedenbeck, 1984. These differ slightly from the original values quoted by Wiedenbeck and co-workers from the ISEE experiment.

Below is a charge by charge summary of our results.

Nitrogen. Nitrogen above the Cerenkov threshold stops near the end of the 2nd and

last total E counter in our telescope. The resulting energy range of analysis is narrow, thus limiting the statistical accuracy of the data. The results obtained here are consistent with earlier results showing a significantly greater abundance of ^{15}N than ^{14}N at earth.

Oxygen. The ^{17}O and ^{18}O abundances that we observe are slightly larger than, but consistent with those originally reported by Wiedenbeck and Greiner, 1981a. It is seen that the secondary production of ^{18}O is ~ 10 x the solar system abundance ratio making it very difficult to achieve a meaningful source abundance determination of this isotope.

Neon. The relative abundances for ^{21}Ne and ^{22}Ne we measure are in good agreement with those reported by Wiedenbeck and Greiner, 1981a. ^{21}Ne is consistent with being all secondary and the source abundance ratio ^{22}Ne/^{20}Ne that we derive is ~ 4 x the solar system value in agreement with earlier measurements.

Magnesium. The relative abundances of ^{25}Mg and ^{24}Mg we measure are again consistent with, but slightly smaller than those originally reported by Wiedenbeck and Greiner, 1981a. (They agree even better with the average abundance ratios summarized by Wiedenbeck, 1984 - see Table II) These slightly lower abundance fractions - coupled with a secondary production which appears to be 20 - 40% larger than that used by the above authors leads to cosmic ray source abundances of these nuclei that are 1.43 ± 0.50 x the solar system ratio for ^{25}Mg/^{24}Mg, and 1.24 ± 0.28 x the solar system ratio for ^{26}Mg/^{24}Mg. These values are lower than those originally reported by the above authors, but are in agreement within the quoted ± 1 σ experimental errors. They are also consistent with cosmic ray source to solar system ratios of one.

Aluminum. The fraction ^{26}Al/^{27}Al of 2.2 ± 1.8% that we measure compares with the fraction of 3.6 ± 2.9% reported by Wiedenbeck, 1983.

Silicon. The fractions we measure for ^{29}Si and ^{30}Si are about 1 σ lower than those originally reported by Wiedenbeck and Greiner, 1981b. For the secondary production of these isotopes we obtain ~ 30-40% more than appears to have been obtained by the above authors. This leads to cosmic ray source fractions of these isotopes which are 0.79 ± 0.42 and 0.82 ± 0.58 x the solar system values respectively. These values are ~ 2 σ below the original values quoted by the above authors. About 1 σ of this difference is due to the larger secondary production we use.

Sulpher. For ^{32}S our source abundance fraction is ~ 1 σ lower than that reported by Wiedenbeck, 1984. In arriving at a source abundance we use a secondary production ~ 33% larger than that which appears to have been used by Wiedenbeck. The actual cosmic ray source abundance ratios we find for both ^{33}S and ^{34}S are consistent with zero. This is not a realistic value, however, since the interstellar secondary production is ~ 5 x the source abundance ratio for ^{34}S and the experimental errors in all measurements to date are greater than the source abundance fraction itself.

Argon & Calcium. Both of these charges are somewhat different than the previous charges discussed. Individually they are dominated by one rather rare isotope in the source, ^{36}Ar or ^{40}Ca and the possible source abundances of the other isotopes are expected to be completely dominated by interstellar secondary production if we consider solar system abundance fractions. The isotopic abundance fractions that we measure as shown in Table I are indeed consistent with purely secondary production with the exception of ^{36}Ar and ^{40}Ca. The fractions of these isotopes we measure are ~ 1.5 x larger than expected for pure solar system abundances however. This could be suggestive of a somewhat larger abundance of these isotopes relative to Fe in the cosmic ray source. Unfortunately we are unable to derive absolute ratios of these isotopes to Fe from this analysis to confirm this suggestion.

3. Summary. In this analysis we find one decisive example of an isotopic abundance difference in the cosmic ray source, ^{22}Ne as has been observed several times before. We also find a suggestion that ^{25}Mg & ^{26}Mg are enhanced but only at the 1 σ level. For

all of the other isotopes we measure, including ^{29}Si & ^{30}Si, our results are consistent with a solar system isotopic composition. About 30% of the difference in the source abundance ratio derived in this paper and those previously reported appears to be due to differences in the cross sections used, the remaining differences are in the experimental results themselves.

4. Acknowledgements. This work was supported by NASA grant NGR - 30-002-052.

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6. Figure Captions.

Figure 1. C x E matrix of events for Oxygen nuclei. Calculated mass lines for ^{15}O, ^{16}O, ^{17}O and ^{18}O are shown.

Figure 2. Mass histograms for N, O, Ne and Mg nuclei.

Figure 3. Mass histograms for Al, Si, S, Ar and Ca nuclei

Fig. 1

Fig. 2

Fig. 3
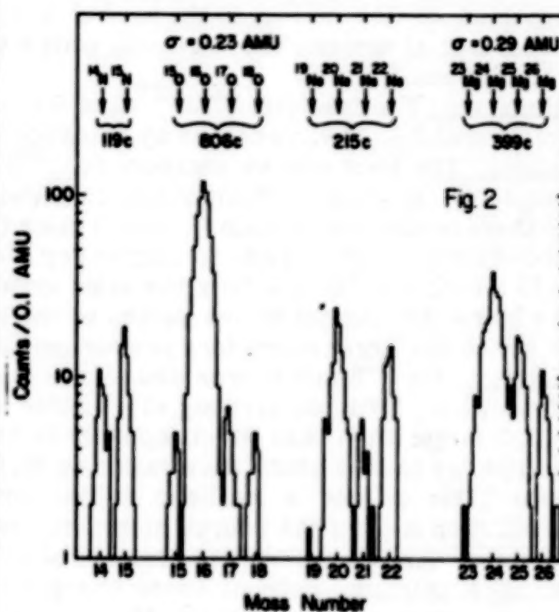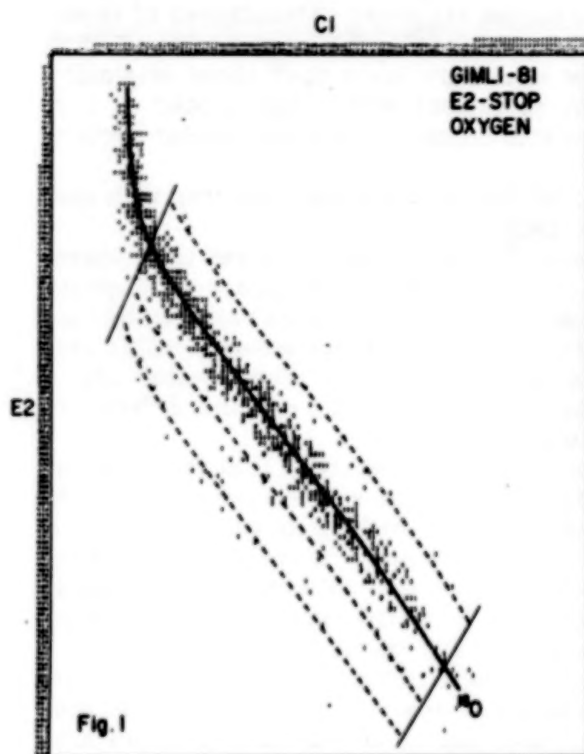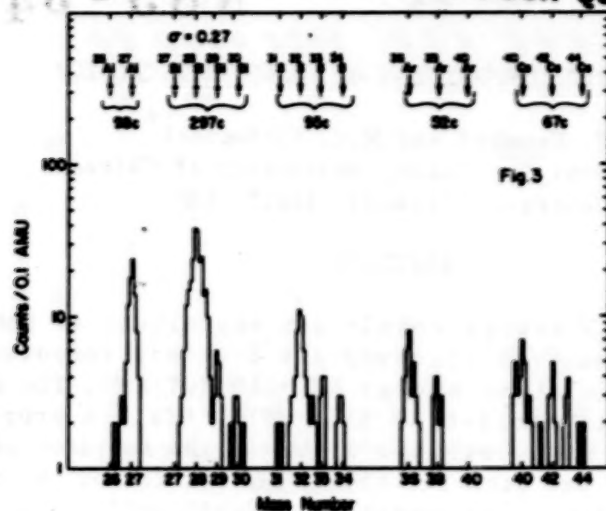
Table I
Isotopic Abundances

Isotope	Energy Interval (MeV/nuc)	Events Observed	% of Charge equal E int.	% of Charge at Top of Atm	Predicted*
¹⁴N	383 - 450	49	39.7	38.2±5.6	
¹⁵N	375 - 430	70	60.3	61.8±5.1	
¹⁶O	390 - 485	752	94.1	94.4	
¹⁷O	386 - 472	22	3.0	2.8±0.6	
¹⁸O	381 - 460	19	2.8	2.7±0.6	
²⁰Ne	410 - 554	121	55.0	54.7	
²¹Ne	408 - 542	23	11.0	10.6±2.1	
²²Ne	401 - 530	67	34.0	34.7±4.0	
²⁴Mg	429 - 610	270	66.5	64.8	
²⁵Mg	425 - 601	66±8	17.0	17.5±2.6	
²⁶Mg	420 - 592	61	16.5	17.7±2.4	
²⁶Al	435 - 635	5±3	5.0	2.2±1.8	
²⁷Al	430 - 627	94	95.0	97.8	
²⁸Si	446 - 642	251	88.1	88.7	
²⁹Si	441 - 637	18±3	6.3	5.9±1.8	
³⁰Si	436 - 632	16	5.6	5.4±1.5	
³²S	462 - 660	64	68.7	69.9	
³³S	457 - 656	14	15.2	14.5±3.9	
³⁴S	453 - 651	15	16.1	15.6±4.1	
³⁶Ar	478 - 678	33	63.5	63.7	67.6
³⁷Ar	474 - 674	2	3.8	2.6±2.0	12.8
³⁸Ar	470 - 669	16	30.8	31.4±8.7	30.9
³⁹Ar	466 - 665	0	0.0	0.0	0.0
⁴⁰Ar	462 - 660	1	1.9	2.2±2.2	5.7
⁴⁰Ca	494 - 697	31	46.1	46.9	30.8
⁴¹Ca	490 - 692	3	4.5	4.1±2.7	6.2
⁴²Ca	486 - 688	16	24.0	23.8±6.6	22.0
⁴³Ca	482 - 684	10	15.0	14.3±5.1	19.8
⁴⁴Ca	478 - 680	7	10.4	10.9±4.4	21.2

* Assuming (³⁶Ar/⁴⁰Ca)₅ = 3.0%, (⁴⁰Ca/⁴⁴Ca)₅ = 6.0%

TABLE II
Isotope Fractions

Ratio	This Measurement (%)	Wiedenbeck, 1984 (%)	Secondary Production (%)	Cosmic Ray Source (%)	Solar System (%)
¹⁷O/¹⁶O	2.9±0.7	1.7±0.4	2.1	0.8±0.6	-
¹⁸O/¹⁶O	2.8±0.7	1.9±0.2	2.1	0.7±0.6	0.2
²¹Ne/²²Ne	19.4±4.1	21±5	20.5	-1.1±4.5	0.3
²²Ne/²⁰Ne	63.4±8.6	58±6	16.5	46.9±9.0	12.2
²⁵Mg/²⁴Mg	27.1±4.4	27±4	8.6	18.5±4.6	12.9
²⁶Mg/²⁴Mg	27.4±2.6	27±3	10.1	17.3±4.0	14.2
²⁹Si/²⁸Si	6.9±2.0	13±2	3.3	3.6±2.7	5.1
³⁰Si/²⁸Si	6.4±1.8	7.2±1.7	3.8	2.6±2.3	3.4
³³S/³²S	20.7±5.8	-	20.5	0.2±6.4	0.8
³⁴S/³²S	22.5±6.1	28±8	23.2	-0.7±8.7	4.4

THE ISOTOPIC COMPOSITION OF COSMIC RAY CALCIUM

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ABSTRACT

Data from the high energy cosmic ray experiment on the ISEE-3
spacecraft have been used to study the isotopic composition of
cosmic ray calcium at an energy of ~260 MeV/amu. The arriving
calcium is found to consist of $(32 \pm 6)\%$ ^{40}Ca. A propagation
model consistent with both the light and the sub-iron secondary
element abundances was used for the interpretation of the observed
calcium composition. The measured $^{42}Ca+^{43}Ca+^{44}Ca$ abundance is
consistent with the calculated secondary production, while the
^{40}Ca abundance implies a source ratio of $^{40}Ca/Fe = (7.0 \pm 1.7)\%$.

1. **Introduction**. In the cosmic radiation, most of the elements in the
sub-iron region $(17 \leq Z < 26)$ are predominantly secondary in origin,
resulting from the fragmentation of heavier cosmic ray nuclei during
propagation from the source to the Earth. Calcium is one exception to
this pattern, having a significant contribution from primary cosmic rays,
particularly for the isotope ^{40}Ca, the dominant isotope (~97%) of solar
system calcium [1]. In this paper, we present new measurements of the
galactic cosmic ray calcium isotopic composition and compare them with
measurements made by other experimenters and the values found for solar
system material.

2. **Data**. The observations reported here were taken with the high energy
isotope experiment on the ISEE-3 spacecraft during the time period from
August 1978 to April 1981. The energy range for calcium is approximately
170 to 380 MeV/amu with an average of approximately 260 MeV/amu. Cuts
were made on the data to eliminate nuclear interactions in the instrument
and to choose only those events which have well determined trajectories.
In addition, only those particles having incident angles of less than 15
degrees with respect to the detector normal were used in the data set
presented here in order to obtain the best mass resolution compatible
with the desired statistical accuracy.

For calcium, a direct measure of the instrument resolution can be
obtained from a comparison with the adjacent element, scandium, which has
a single stable isotope, ^{45}Sc. The scandium mass distribution can be used
as a measure of both the absolute mass scale and the resolution expected
at calcium.

Figure 1(a) shows the scandium mass distribution in 0.25 amu bins,
along with a best fit Gaussian curve. The Gaussian has a standard devia-
tion of 0.49 amu and the histogram has been adjusted to be centered at
mass 45. The difference between the calculated mean mass and the true
mass was 1.1 amu, and is simply an artifact of systematic errors in the
mass calculation. This value is consistent with the smoothly varying
trend seen for lighter elements and for iron. Figure 1(b) shows the cal-

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cium distribution in 0.25 amu bins, again with a best fit distribution superimposed. This fitted distribution is a superposition of five Gaussian peaks (corresponding to isotopes of mass 40 through 44) with center-to-center spacings of 1 amu and equal widths. The common width and the position of the mass 40 peak were allowed to vary in the fit along with the individual abundances. The deduced resolution was 0.53 amu and an offset of 1.07 amu was needed to center the mass 40 peak.

Although the mass resolution achieved is insufficient to cleanly resolve ^{42}Ca, ^{43}Ca, and ^{44}Ca, the relative lack of ^{41}Ca permits separation of the dominantly primary ^{40}Ca from the dominantly secondary ^{42}Ca, ^{43}Ca and ^{44}Ca. Comparison with the scandium mass distribution cleary demonstrates that the structure seen in the calcium histogram is due to actual abundance variations and not just statistical fluctuations since the width of the ^{45}Sc peak, 0.49 amu, is significantly less than the overall width of the calcium distribution and is consistent with the resolution determined from the calcium data. In addition, the scandium permits an unambiguous determination of the absolute mass scale verifying that ^{40}Ca is assigned the correct mass.
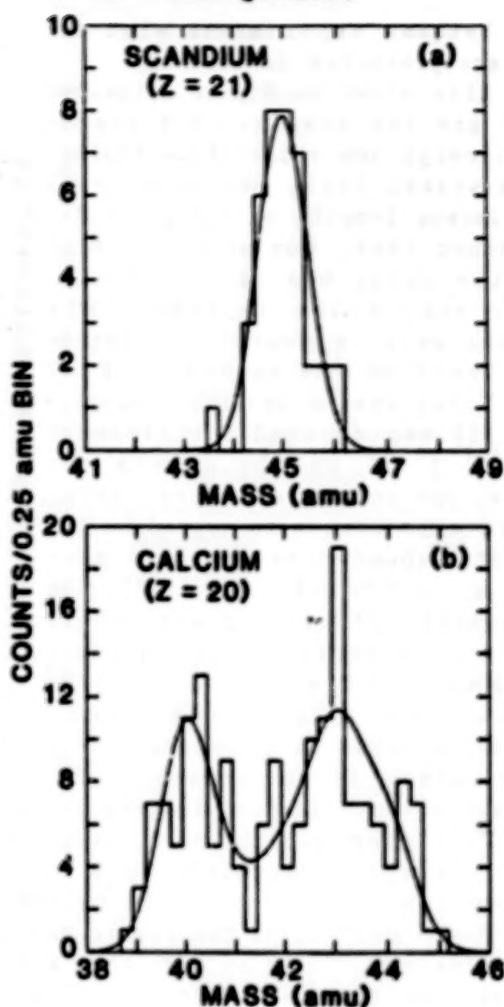
Figure 1

3. **Discussion.** Because ^{42}Ca, ^{43}Ca, and ^{44}Ca are not clearly separated in this data set, determination of their individual abundance values requires a more detailed analysis of the resolution systematics. However, a way of viewing these data which is less dependent on the details of the peak shapes is to divide the calcium into primary species (^{40}Ca) and secondaries (^{42}Ca, ^{43}Ca and ^{44}Ca) since the low abundance of ^{41}Ca permits resolution at this scale. Our data imply an arriving cosmic ray calcium composition of (32 ± 6)% ^{40}Ca and (60 ± 6)% 'secondary group', as defined above. Since the ^{41}Ca could be expected to be sensitive to the exact peak shape used, no value is reported here.

These isotope fractions are plotted in Figure 2, along with the results reported by other experimenters [2, 3, and 4]. Since the New Hampshire [3] and Minnesota [2] groups presented individual isotopic abundances, the uncertainties shown for their $^{42}Ca+^{43}Ca+^{44}Ca$ measurements are estimated from the individual errors that they reported. Additionally, Tarlé et al. [4] did not present an explicit $^{40}Ca/Ca$ ratio. The value used here is the result of counting events on their calcium mass histogram. As can be seen from Figure 2, there is reasonable agree-

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ment between experiments when the data are presented in this way.

Also shown in Figure 2 (dashed line) are the results of a cosmic ray propagation calculation employing a nested leaky box model with mean escape lengths of 1.5 g/cm² for the inner leaky box and 3.0 g/cm² for the outer box (H:He = 10:1). Solar modulation is taken into account using a numerical integration based on the method of Fisk [5]. Solar system isotopic composition [1] was assumed for elements with $Z \geq 19$ in the cosmic ray source, and source elemental abundances were chosen to reproduce the elemental abundances observed near Earth at 70-280 MeV/nucleon [6]. The pathlength values used were those needed to simultaneously reproduce the observed B/C and the (Sc+V)/Fe ratios at these energies.

Figure 2

The shaded areas on the figure indicate the fraction of each group which is primary. As can be seen, the division into ^{40}Ca and $^{42}Ca+^{43}Ca+^{44}Ca$ provides a very clean separation between primary and secondary calcium.

This propagation model, based on light and sub-iron secondary elements, is also compatible with the observed abundance of calcium secondaries (Figure 2). The present observations imply that the ratio $^{42}Ca+^{43}Ca+^{44}Ca/^{40}Ca$ in the cosmic ray source does not exceed its solar system value (0.03) by more than a factor of ~30. Although our measured abundance of this secondary group does not require a finite source abundance of any calcium isotope other than ^{40}Ca, separation of this group into its constituent isotopes is required to firmly establish this conclusion.

Because the calcium elemental abundance observed at Earth is 60% secondary while the isotope ^{40}Ca is only 4% secondary, the use of the calcium isotope information can significantly reduce the uncertainties involved in deriving the source abundance of calcium. If we ignore the isotope information and employ only the elemental abundances of [6], we find that the source Ca/Fe ratio is (8.2 ± 7.8)%, where the uncertainty includes the effects both of observation errors and of propagation errors [7]. The latter source of uncertainty, due mostly to assumed 35% correlated errors in fragmentation cross sections, is found to dominate. If the ^{40}Ca isotope fraction is used in conjunction with the elemental abundances, we obtain, at the source, $^{40}Ca/Fe$ = (7.0 ± 1.7)%. The relative uncertainty in this source ratio is only 24%, as compared with the 95% uncertainty in the ratio obtained using elemental abundances alone. Furthermore, the uncertainty in our deduced $^{40}Ca/Fe$ source ratio is dominated by the observation errors (rather than by uncertainties in the propagation calculation), so future improvements in the resolution and statistical accuracy of calcium isotope measurements will further improve the accuracy of the deduced ^{40}Ca source abundance. In Table 1 we compare our value of the $^{40}Ca/Fe$ source abundance ratio with values reported by
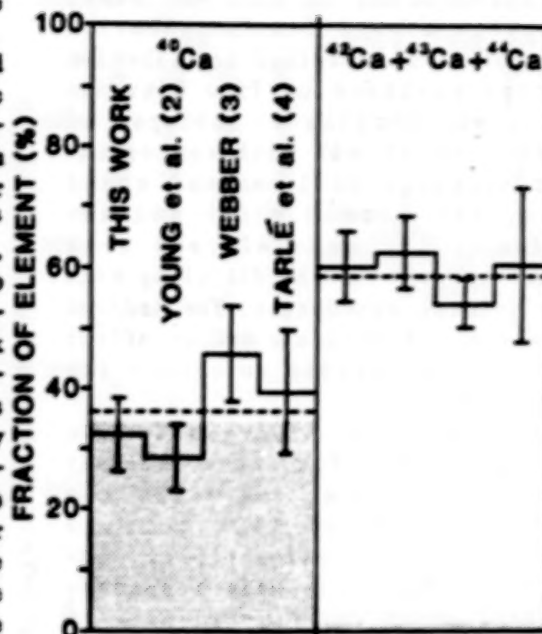
other investigators. While these values are all in reasonable agreement, one must exercise caution in comparing them because the specifics of the propagation models and error calculations used by the various authors differ.

The ratios of cosmic ray source elemental abundances (GCRS) to the corresponding solar system values (SS) have been found to be reasonably well organized by the first ionization potential of the element (e.g. [8], and references therein), although other possible ordering parameters (such as volatility [9]) have been

TABLE 1

Derived Values of ^{40}Ca/Fe in the Cosmic Ray Source

Value	Reference
7.0 ± 1.7 %	this work
6.2 ± 1.1 %	2
8.8 ± 1.6 %	3
5.9 ± 1.9 %	4

proposed. By combining our ^{40}Ca/Fe source ratio with the value of this ratio in the solar system (6.73% [1]), we find $(^{40}Ca/Fe)_{GCRS}/(^{40}Ca/Fe)_{SS}$ = 1.04 ± 0.25. Two general functional forms have been suggested for representing the dependence of such ratios on first ionization potential. The first is an exponential dependence of the form $GCRS/SS = exp(-I/I_o)$, while the second is a step function where all elements with low first ionization potential (I ≤ 9 eV) have one value and all those with high first ionization potential have a single, lower value. Calcium has a first ionization potential of 6.1 eV and for iron the value is 7.9 eV. Our present results are thus consistent with the step-function dependence. They are consistent with an exponential dependence only if a relatively low value of the parameter I_o is used. Brewster et al. [10] have reported the results of two different exponential fits. One, excluding the light noble gas elements, has I_o = 3.47 eV, and implies that the GCRS ^{40}Ca/Fe ratio should be 1.66 times the solar system value. The other has I_o = 5.6 eV and implies that the ^{40}Ca/Fe enhancement should be 1.37. These two predictions exceed our deduced value by 2.5 and 1.3 standard deviations, respectively. While discrepancies at this level for a single element are not sufficient to rule out such exponential dependence on first ionization potential, they do suggest that extreme exponential dependencies are unsatisfactory in this case or that some other ordering parameter may be more appropriate.

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A NEW ANALYSIS OF COSMIC RAY ISOTOPES
AT 3 GeV/n FROM HEA03-C2 DATA

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ABSTRACT

We present results on mean masses of cosmic rays at energy
about 3 GeV/n, for Ne, Al, Mg, Si, S, Ca., and Fe, derived from
the data collected by the Danish-French experiment C2 on board
HEA03. We used a method based upon comparison between observed
transmission function and a predicted one computed from a geoma-
gnetic field model. We find enhancement factors of 2.9 +-.7 for
22Ne/20Ne, 2.1 +-.4 for (25Mg+26Mg)/24Mg, and 1.6 +-.8 for
(29Si+30Si)/28Si at GCRS when compared to LG.

Introduction

Cosmic ray isotopic rather than elemental composition is a
major clue to the understanding of cosmic rays history because
while the elemental source composition can a priori be interpreted
in terms of any kind of scenario involving either atomic or nu-
clear processes, isotopic anomalies almost certainly imply speci-
fic nucleosynthetic processes (at least for Z > 4). If elemental
abundances and spectra are now well established /1,2/ and show
remarkable similarities with Solar System abundances and Solar
Energetic Particles /3/ , isotopic composition measurements avai-
lable at low energy (<1 GeV/n) show significant differences when
compared to Local Galactic material (see /4/ for a review).
Measurements at higher energy present the advantage to be less
dependent upon solar modulation; however they are more difficult
to perform . Peters /5/ has developed a method allowing determi-
nation of mean masses with the help of the geomagnetic field;
analysis of HEA03-C2 data were already performed using the trans-
mission function method /6,7/ but dealt with part of the data
because of geomagnetic selections. In this study a different
approach is used: we also start from the observed transmission
function (OTF) which reflects the filtering effect of the geoma-
gnetic field upon relativistic particles; this effect depends
upon rigidity so that isotopes with different A/Z ratios show
different OTF. The point of our method is that we compute the
theoretical filtering effect in the frame of a geomagnetic field
model (MAGSAT 4/81); we are then able to predict the various
transmission functions corresponding to all possible isotopic
fractions. Isotopic composition is derived by adjusting the pre-
dictions to the actually observed transmission function.

Method

Building an OTF requires the knowledge for each detected par-
ticle of the momentum by nucleon P and the main cut-off Rc cor-
responding to the position and direction of arrival in the
instrument /6,7/. P is measured by the instrument and Rc is com-
puted with a trajectory tracing method /8/. The number of parti-
cles observed with momentum by nucleon p' at a main cut-off Rc is
given by :

$$d^2N/dp \cdot dRc = Tex(Rc) \cdot \sum_i \int_p F(Rc,Ri) \cdot \beta i \cdot f(p) \cdot P(p,p') dp \qquad (1)$$

with $Ri = Ai.p/Z$. $Tex(Rc)$ is the exposure time at main cut-off Rc, $f(p)$ the differential momentum spectrum of the element, βi the isotopic fraction of isotope Ai , and $P(p,p')$ the momentum resolution function of the instrument. $Tex(Rc)$ and $f(p)$ are derived from the data. $F(Rc,R)$ is the mean geomagnetic filter function at main cut-off Rc. Let us recall that a particle can reach a given point of observation in a given direction only if it passes the geomagnetic field barrier, which may be described as a filter function $ff(R)$ which only depends upon rigidity. For each point and direction there exists a main cut-off Rc so that $ff(R) = 1$ if $R > Rc$. For $R < Rc$ one may have either $ff(R) = 1$, if the associated trajectory is allowed, or 0 if it is forbidden (penumbra region). The mean filter function $F(Rc,R)$ represents the average of all filters $ff(R)$ at a given Rc. Practically, for each particle, we compute Rc as the highest forbidden rigidity; then we randomly select 30 rigidities in the penumbra region for which we compute if they are allowed or forbidden. The mean filter function $F(Rc,R)$ is obtained by averaging all these statistical penumbra at given Rc. Preliminary calculations have shown that the penumbra vanishes below $.75\ Rc$ for the region of interest here. To avoid biases in the computation of mean filters only particles with $p/Rc > .6$ were selected. Predicted transmission functions corresponding to given isotopic fractions are computed by summation of (1) at constant p/Rc.

Determination of experimental parameters

We analysed data with rigidity between 7 and 9 GV and momentum between 3.2 and 6.1 GeV/cn; the fit region ($p/Rc = .4$ to $.52$) corresponds to a mean energy of 3 GeV/n. 21 mean filters were computed by step of 0.1 GV from 7 to 9 GV. The instrumental function $P(p,p')$ is taken as a gaussian function with a standard

deviation S. To account for a possible drift in momentum we introduce another parameter, D, so that p observed = D times p true. To determine S and D oxygen is used as a reference element assuming 96% of 160, 2% of 170, and 2% of 180. However these two parameters alone do not allow us to account for the OTF of oxygen which is systematically higher than prediction in the penumbra. The discrepancy is removed by assuming a scaling factor SF by which we multiply all computed $F(Rc,R)$ in the region $R/Rc < 1.0$. The three parameters are simultaneously optimized by minimizing the chi² between observed and predicted transmissions. Values of .990, 4.3%, and 1.18 are respectively found for S,D and SF. Fig 1 shows the agreement between predicted and observed transmission functions for oxygen. The shift of 1% between actual and observed momentum, which is compatible with the error on the measurement of the refractive index of the Cerenkov detector, indica-

Fig 1: Observed transmission function (+), and best fit prediction (full line).

tes that the geomagnetic field model gives an accurate estimate
of the main cut-off. The value of SF shows that more than 80% of
the penumbra is well accounted for by the model; the missing 20%
may come either from complex trajectories not handled properly by
the tracing program, or from possible instrumental background. S
is twice higher than the value expected from the statistics of
Cerenkov photoelectrons alone. It reflects other effects like
delta rays, and a possible slight distorsion in the shape of the
estimated mean filters.
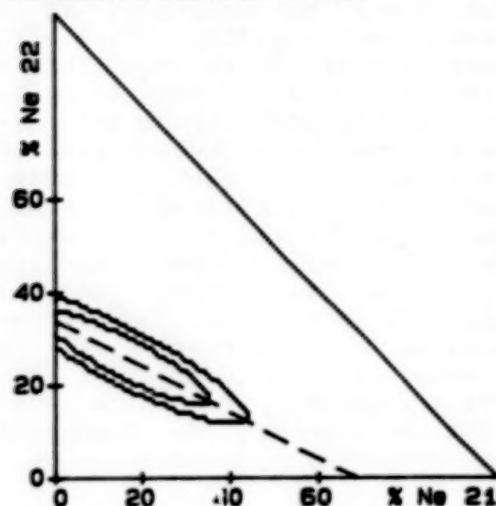
Fig 2: 68 and 90% confidence
level regions for observed
fractions of 21Ne and 22Ne.
Broken line is the line of
mean mass 20.68 .

Results

The same parameters D and SF
derived from O were used to analy-
se higher elements. A $1/Z$ depen-
dence of S was found suitable;
it's value has only a little
influence on mean masses. We com-
puted all chi' between OTF and
prediction for all possible isoto-
pic composition; the minimum chi'
gives the measurement. Contours
of 68 and 90% confidence level
from chi' analysis are plotted in
fig 2 for Ne isotopes. The
strongly elliptical form of the
contours is the sign of highly
correlated parameters; the major
axis of ellipses are aligned with
the equal mean mass lines, sho-
wing that the fundamental parame-
ter of the method is the mean
mass. Results are therefore given
as mean masses with quoted errors
corresponding to a chi' increase
of 1.0 from minimum chi'. A check is provided by Na (which has a
single isotope), 311 Na are predicted, in agreement with the 324
observed in the fit region. In table 1 we report our results to-
gether with the mean masses obtained from a propagated solar
source (SS) composition. S,Ca, and Fe have an observed mean mass
quite compatible with a propagated SS composition, while Ne (
confirmed by /9/, also from HEAO3-C2 data, but with a different
method), Mg, and possibly Si are found to be neutron enriched.

Discussion

Results were propagated back to Galactic Cosmic Ray Sources
(GCRS) in a leaky-box model, including energy losses, radioactive
decay, in a pure H (density 0.3 cm⁻³) I.S.M. . An escape length
equal to 22.R-0.6 (6.2 g/cm⁻² at 3 GeV/n), and a modulation para-
meter ϕ = 600 MV were assumed according to /2/. We also assume 0
% of 21 Ne, an equal fraction of 25 and 26Mg, an equal fraction
of 29 and 30Si in GCRS. Errors only include statistical measure-
ment uncertainties. In table 2 the ratios of GCRS abundances
to Local Galactic (LG, from /10/) are given for Ne, Mg and Si.
It is seen that Ne and Mg are definetely neutron enriched in
GCRS, with enhancement factors comparable to the low energy re-
sults of 4.1 (+.8,-.6) for Ne, and 1.6 (+.3,-.2) for Mg, at ϕ 200
MeV/n, /4/. There is therefore no evidence for an energy depen-
dence of these isotopic source anomalies. The poorer resolution
for Si isotopes does not allow us to distinguish between a LG
composition or a neutron rich one. These results are compatible

with the suggestion that the bulk of Cosmic Rays is injected in the acceleration process from solar like stellar coronae with normal abundances, while a minor part of it (2-3 %) would come from sites having experienced more evolved nucleosynthesis. Wolf-Rayet stars could explain the neutron rich component for Ne and Mg, as well as the overabundance of C but predicts a normal isotopic composition for Si, /11/. If the enhancement factor for Si, found at low energy, is confirmed, metal rich supernovae could also contribute to GCRS isotopic anomalies, /12/. Isotopic ratios such as 36S/32S, 57Fe/56Fe, 58Fe/56Fe, still to be measured, could help distinguishing between various models.

Table 1: Observed mean masses at 3 GeV/n

Element	Number in the fit region	Observed mean mass	Propagated SS composition
Ne	1681	20.68 (+-.06)	20.48 +-.08
Mg	1910	24.59 (+-.06)	24.42 +-.04
Al	323	26.91 (+.09,-.16)	26.90 +-.03
Si	1373	28.25 (+-.07)	28.19 +-.035
S	275	32.70 (+.22,-.20)	32.56 +-.16
Ca	210	41.80 (+.35,-.30)	41.65 +-.22
Fe	1114	55.75 (+-.20)	55.82 +-.03

Table 2:

Enhancement factors GCRS ratios/LG ratios		
22Ne/20Ne :	2.88 (+.77, -.65)
(25Mg + 26Mg)/24Mg :	2.03 (+.49, -.42)
(29Si + 30Si)/28Si :	1.55 (+.84, -.74)

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THE ENERGY DEPENDENCE OF THE NEON-22 EXCESS IN THE COSMIC RADIATION

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Introduction

It has been recognized now for some time that the heavy neon isotope, neon-22, is overabundant by a factor of 3 to 4 with respect to neon-22 in the cosmic ray source compared to the ratio of these isotopes in the Solar System (1-8).

In view of the otherwise remarkable similarity of the chemical composition of the cosmic ray source and the composition of the Solar Energetic Particles (9), the anomaly regarding the neon isotopes is so much more striking.

The observed excess of neon-22 is too large to be explained as a result of the chemical evolution of the Galaxy since the formation of the Solar System (10).

Further information on the origin of the neon-22 excess may come from a comparison of the energy spectra of the two neon isotopes. If the cosmic radiation in the solar neighborhood is a mixture of material from several sources, one of which has an excess of neon-22, then the source energy spectra of neon-20 and neon-22 may differ significantly.

Data

We have compiled the available data on the neon-22 to neon-20 ratio as function of energy. The data are shown in figure 1a. The observed ratio is sensitive to the level of solar modulation at the time of observation; therefore we show in figure 1b the same data extrapolated to zero solar modulation (the interstellar flux). We have used the force field approximation for the solar modulation and have applied a correction for each data point corresponding to the relevant period of observation.

Finally figure 1c shows the calculated source ratio corresponding to each data point. For this calculation we have used the propagation model described in (11).

The error bars in figure 1 are everywhere those of the experimenters. We have not attempted to assign errors to the correction for solar modulation or for the propagation calculation. The uncertainties in these corrections are appreciable despite the fact that we are only concerned with a flux ratio, not with absolute fluxes.

We note however, that the best fit straight line to the source fluxes has a slope of - 0.031 ± 0.040, i.e. it is consistent with an energy

independent source ratio, even considering only the original statistical errors on the data points.

Discussion

The best fit, energy independent, source ratio of neon-22 to neon-20 is 0.35 ± 0.05. This is nearly three times the solar value of 0.12.

The apparent similarity of the source energy spectra for the two neon isotopes speaks in favor of a common acceleration mechanism for both, i.e. for the neon-22 excess already existing in the source material before the acceleration.

Since, as mentioned above, a neon-22 excess of the observed magnitude is unlikely to be a general feature of the present day interstellar medium, we are led to conclude that <u>either</u> there is a direct connection between the nucleosynthesis chain leading to excess neon-22 and the cosmic events leading to particle acceleration, <u>or</u> the local cosmic ray flux is dominated by a single source with an accidental excess of neon-22.

A dominance of a single source is incompatible with the observed high degree of isotropy of the cosmic radiation. The local source picture is therefore only tenable if restricted to the heavy nuclei; the bulk of the cosmic ray nucleons, in the hydrogen/helium component, must in any case arise in a multitude of sources distributed in the Galaxy (12).

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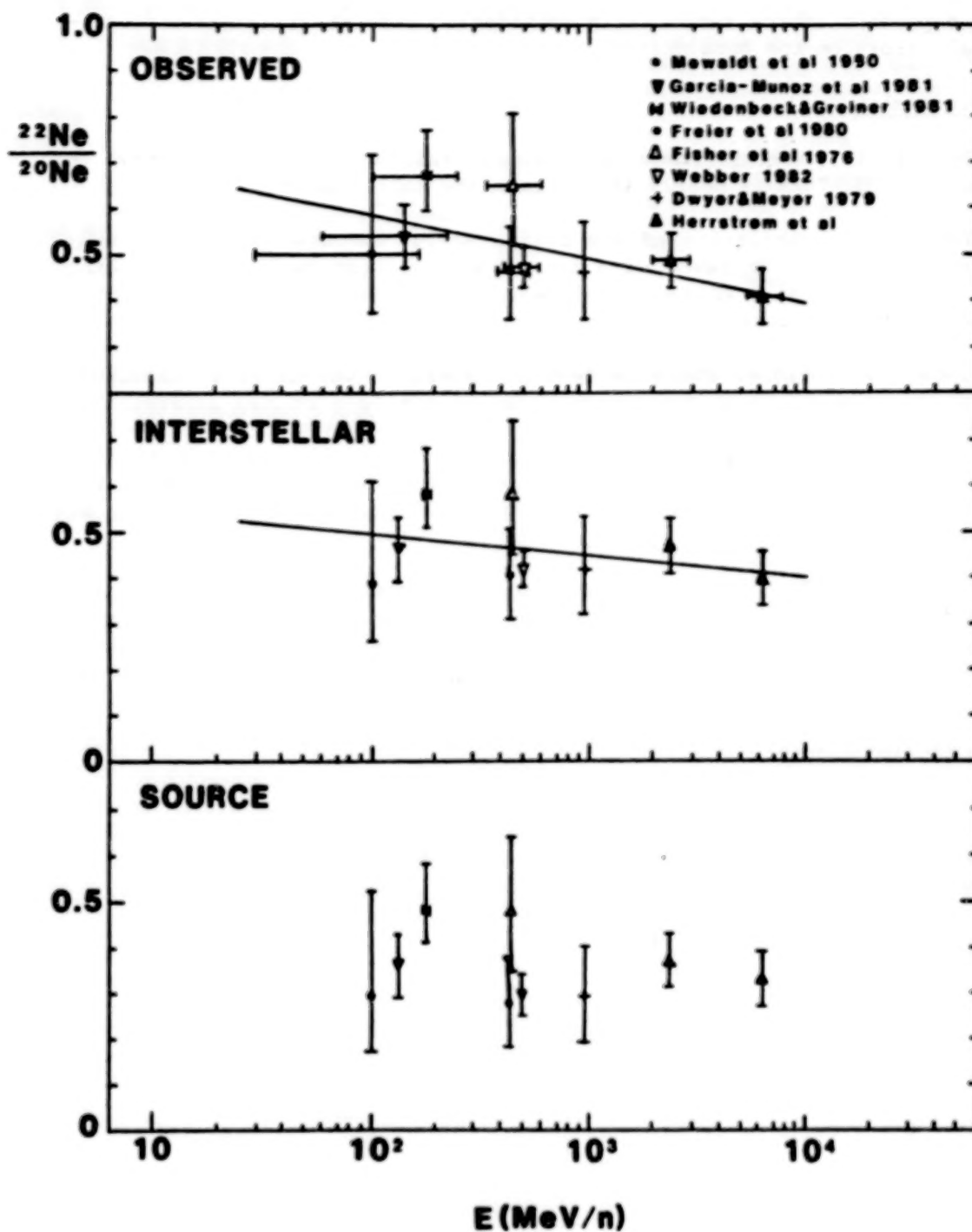
Fig. 1. The neon-22 to neon-20 ratio as function of energy.

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INITIAL RESULTS FROM THE CALTECH/DSRI BALLOON-BORNE ISOTOPE EXPERIMENT

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ABSTRACT

The Caltech/DSRI balloon-borne High Energy Isotope Spectrometer Telescope (HEIST) was flown successfully from Palestine, Texas on 14 May, 1984. The experiment was designed to measure cosmic ray isotopic abundances from neon through iron, with incident particle energies from ~ 1.5 to 2.2 GeV/nucleon, depending on the element. During ~ 38 hours at float altitude, > 10^5 events were recorded with $Z \geq 6$ and incident energies $\gtrsim 1.5$ GeV/nucleon. We present results from the ongoing data analysis associated with both the pre-flight Bevalac calibration and the flight data.

1. Introduction. The experiment described here is a joint undertaking by Caltech and the Danish Space Research Institute. A large-area (geometric factor ~ 0.25 m^2 sr) balloon-borne instrument has been developed to measure cosmic-ray isotopic abundances from neon through iron, with incident particle energies from ~ 1.5 to 2.2 GeV/nucleon, depending on the element (1). The experiment was first flown on 14 May, 1984, from Palestine, Texas. Prior to flight, the detector was exposed to beams of carbon, neon, argon, and manganese at the Berkeley Bevalac, with the latter exposure providing the principal calibration for the instrument. Preliminary results associated with the development of mapping techniques and position-determining algorithms are discussed, with application to flight data.

2. Instrument Description. The experiment employs either Cerenkov-ΔE-Cerenkov or Cerenkov-total energy techniques for isotope resolution (see reference 1), depending on whether the incident particle traverses the entire detector, or stops at an intermediate position in the instrument. Figure 1 shows a schematic diagram of the detector. A stack of twelve NaI(Tl) disks (each nominally 2 cm thick, 52 cm diameter; 87.2 gm/cm² total thickness) directly measures the energy change ΔE for an incident particle. Two Cerenkov counters (C1 and C2), measure the change in Lorentz factor, $\Delta\gamma = \gamma_1 - \gamma_2$, for the event. For a stopping particle $\gamma_2 = 1.0$. Mass M is obtained from:

$$M = \Delta E / \Delta \gamma$$

Each disk making up the stack is viewed by six individually digitized photomultiplier tubes (PMT). This permits not only a measurement of the energy deposition per layer, but through intercomparison of the six PMT responses, yields the particle's position in that layer (2,4). Because of the large amount of material

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necessary to slow down the high-energy nuclei, typically 85% of the incident particles meeting the trigger requirements will undergo charge-changing fragmentation reactions in the detector. For the NaI stack, these events are removed through a comparison of the individual layer responses. Plastic scintillators (S1 and S2), define the geometry factor, and provide additional rejection against events fragmenting within the Cerenkov counters.

The top Cerenkov counter consists of a mosaic of 48 aerogel radiators of refractive index n ~ 1.1, while the bottom counter employs a combination of teflon (n = 1.34) and Pilot 425 (n = 1.49). Results associated with the ^{56}Mn Bevalac calibration of the aerogel counter have been presented previously (3).

In its flight configuration, the detector and associated electronics are mounted in an insulated pressure vessel. An on-board evaporative cooling system is employed to maintain constant detector temperature, minimizing the need for thermal corrections in the data. Along with housekeeping information, the 108 digitized PMT outputs are recorded on-board using two video recorders, and are also transmitted to the ground through a telemetry link for real-time analysis.

3. Flight Details. The experiment was flown from Palestine, Texas on 14 May, 1984, using a 17.2×10^6 ft^3 Winzen balloon. The instrument maintained float altitude for ~ 38 hours, at a typical atmospheric depth of ~ 5.5 gm/cm^2. During the flight, the geomagnetic cutoff ranged from ~ 4.5 to 5.5 GV. The experiment was recovered with minimal damage to the instrument.

For the flight, ~ 4.25×10^5 events were recorded, which included > 10^5 events with $Z \geq 6$ and kinetic energy > 1.5 GeV/nucleon. While only a fraction of the events will be usable for isotope analysis, the remainder are being employed for in-flight mapping of the detector, gain balancing, and stability checks.

Analysis of the flight data has shown that with minor exceptions, all systems performed as designed. The evaporative cooler maintained a constant detector temperature of $25.0 \pm 0.5°C$ for the majority of the flight, with a gradient across the NaI stack of $\leq 0.2°C$. Examination of threshold settings and detector gains and offsets, have indicated an overall average stability for the flight of better than 1%.

4. Data Analysis. One innovation in this experiment is that the NaI stack provides both trajectory and energy loss information for an incident particle. However, this requires that the response of the individual disks making up the stack be accurately mapped. Previous analysis results have been presented based on the November, 1982 Bevalac calibration, which employed a beam of ^{56}Mn ions, at 1.75 GeV/nucleon (4). Those results were based on analysis of data from two central regions of the instrument. Our primary analysis objective has been to use the ^{56}Mn calibration data to generate full-disk response maps of each PMT viewing each stack layer, and to obtain full-disk maps of the response ratios with various PMT combinations, for position determination.

The response maps for each PMT are generated using an overlay of 1 cm bins on each NaI disk. Typically, the response of a single PMT varies by a factor of 5 to 7 across the disk. The current mapping technique uses calibration data to assign an average response to the center of each bin. For each event, a multi-point interpolation process is employed to obtain correction factors from the maps, with the final response generated from a weighted average over all six PMT's viewing the disk.

Figure 2 shows a histogram of the normalized energy loss (response) for layer 1, averaged over the entire disk. The resolution achieved of ~ 2.8% FWHM is only slightly worse than the 2.4% previously reported for central regions of the stack (4). We estimate that Landau fluctuations account for approximately one-half the distribution width. Results for layers 2 and 3 exhibit similar distributions, with a FWHM of ~ 3.0%. Additional refinements in the mapping technique are expected to improve the energy

resolution further.

In addition to generating full-disk response maps, work is progressing on developing position determining algorithms for the disks. Position resolution is obtained from the calibration data, by comparing the measured event position obtained from Bevalac wire-chamber data, and that inferred from algorithms employing ratios of disk PMT responses. The use of PMT response *ratios* effectively removes the energy dependence from the position determination. Currently, six ratio maps are generated for each NaI disk, using a 1 cm spatial grid. The maps employ ratios of opposite sums of two and three adjacent PMT's viewing each disk. Intermediate positions are obtained using an interpolation process. For a given event, the best estimate of particle position is determined from an algorithm which minimizes the difference between the mapped ratios and the measured event ratios.

Figure 3 shows the difference distribution for a single position coordinate (ΔX), as determined from ^{55}Mn calibration data averaged over approximately the central two-thirds area of layer 1. The central portion of the distribution has a FWHM of 4mm, in good agreement with the results previously presented, that were limited to data near the stack axis (4). Similar results are obtained for the orthogonal coordinate ΔY. Combining both position coordinates for layer 1 produces the difference distribution shown in Figure 4, where:

$$\Delta R = (\Delta X^2 + \Delta Y^2)^{\frac{1}{2}}$$

From these results, the rms position resolution for layer 1 is found to be of order 3mm. In extending the analysis to deeper stack layers, the distribution broadens to ~ 4.4mm by layer 5. We consider these results as upper limits to the intrinsic stack resolution, in that contributions from wire-chamber uncertainties and multiple Coulomb scattering have not yet been unfolded from the data.

5. Discussion. While we anticipate further improvement in the analysis results described here, our results for energy resolution are already consistent with the design goals for isotope resolution in the instrument. In particular, if we extrapolate these results to the full 12 layers of the stack for stopping ^{55}Mn, the expected contribution to mass error from uncertainty in ΔE is of order 0.3%. This uncertainty results in an associated mass error for the instrument of ~ 0.19 amu for Mn at the Bevalac energies, with a correspondingly smaller uncertainty for the lighter elements.

Prior to the detailed analysis of the flight data, the maps and position-determining algorithms developed from the ^{55}Mn Bevalac exposure must be extended to the remaining stack layers. Concurrent with this effort, we are optimizing techniques for trajectory determination, and extending the position-determining algorithms to the outer edges of the disks.

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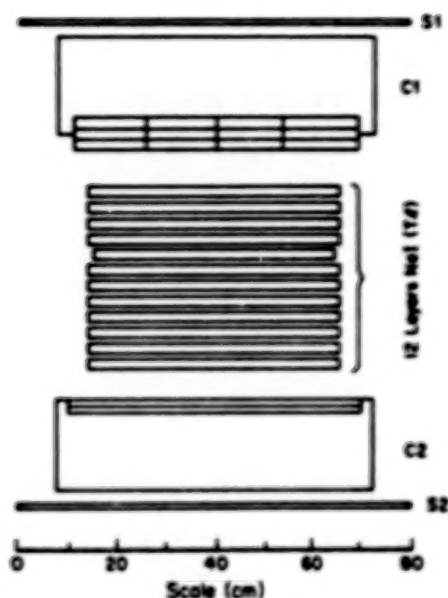
Fig. 1. Schematic diagram of the detector.
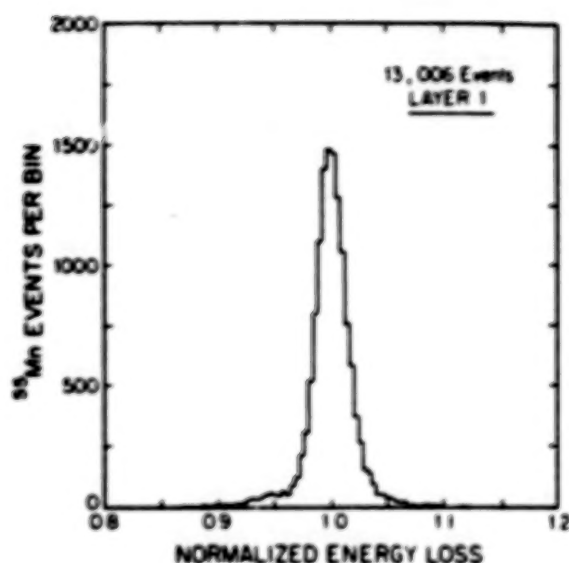
Fig. 2. Layer 1 response distribution for ^{55}Mn, averaged over the full NaI disk.
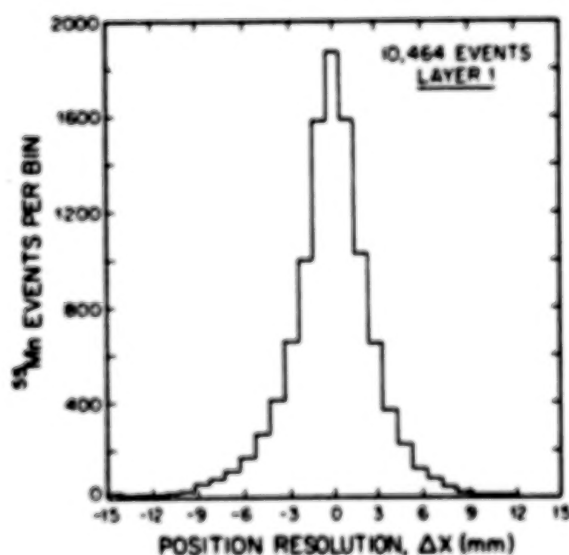
Fig. 3. Difference distribution between a single Bevalac wire-chamber coordinate, and that obtained from layer 1 NaI response ratios, averaged over the central two-thirds area of the disk, for ^{55}Mn ions.
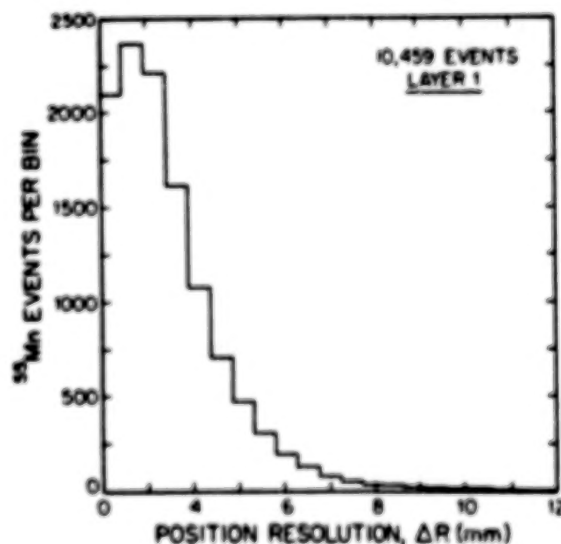
Fig. 4. Difference distribution between Bevalac wire-chamber positions, and those obtained from layer 1 NaI response ratios, averaged over the central two-thirds area of the disk, for ^{55}Mn ions.

THE INNER GRANULOMETRIC DENSITY OF THE TRACKS IN NUCLEAR
EMULSIONS AND ITS APPLICATION TO DETERMINE THE CHEMICAL
SPECTRUM OF PRIMARY COSMIC RAY NUCLIDI.

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1.- Introduction. The classical formula of Lattes, Fowler and
Cüer [1],

$$(1) \quad E = b \, Z^{2a} \, A^{1-a} \, R^{a}$$

which gives the energy E of a non-relativistic nuclide as
function of the atomic number Z , the relative atomic mass
A and the linear residual range R (b and a = constants) is
valid for residual ranges of the order of 2,000 μm under the
assumption that the nuclide itself does not capture electrons
before its stopping point inside the nuclear emulsions. For
a given interval $\Delta R = L$ (referred as a cell in this paper),
with an effective ionizing atomic number Z_{eff} (due to a gi-
ven number of captured electrons) formula (1) becomes,

$$(2) \, \Delta E = b \, Z_{eff}^{2a} \, A^{1-a} \left\{ R_{eff}^{a} - (R_{eff} - L)^{a} \right\}$$

Actually, the linear residual ranges which are determined
with the microscope (here denoted as R_{T}) neither are repre-
sented by R of (1) nor by R_{eff} of (2) because of the effect
of the successive electron captures along the linear residual
range. However, at a given value of R_{T} - or of Z_{eff} - the
expression $R_{T}^{a} - (R_{T} - L)^{a}$ differs from the corresponding
one of (2) as an infinitesimal of second order.

Therefore, if we measure R_{T} and determine ΔE in a cell
$\Delta R = L$, we can obtain the particular value of the expres-
sion $(Z_{eff})^{2a} A^{1-a}$ at R_{T} .

2.- The Method. A direct counting of the number of developed
grains inside a cell $\Delta R = L$ at a given residual range R_{T}
was carried out on tracks of stopping monocharged nuclidi as
those of protons and deuterons. By applying formula (2) with
R_{T} instead of R_{eff} (taking a = 0.588 and b = 0.281 for our
G-5 Ilford emulsions), ΔE was determined and consequently,
also the value w of the energy transferred to each micro-
crystal of $Ag Br$ - involved in the formation of a single
silver developed grain - was obtained.

For $Z \gtrsim 2$, the inner granulometric density is defined by
the ratio between the volume of the track segment of length
$\Delta R = L$ and that one of the single proton developed grain.

The corresponding measurements of diameters of grains and thicknesses of tracks were carried out by strictly applying the Occhialini's Track Profile Method (2).

As it has already shown for protons and deuterons in Table I, the experimental measurements resulted coherent and compatible with the assumption that at a given value of the function $\mathcal{X}$ (Partition Function) given by,

$$(3) \quad \mathcal{X} = R/(Z^{2a} A^{1-a}) = b \; R^a$$

the energy loss of a nuclide involved in the formation of a single silver developed grain which, in turn, is located inside a small part of the track (e.g. $L = 20 \; \mu m$) is the same for any nuclide stopping inside a given plate, independently of the value of Z. This fact together with the value of the inner granulometric density permit us to determine ΔE corresponding to this track segment at the residual range R_r and consequently, to know the magnitude $Z^{2a} A^{1-a}$.

TABLE I

R (μm)	w_p (MeV/grain)	w_D (MeV/grain)
0-20	0.0423 ± 0.0040	0.0400 ± 0.0041
20-40	0.0204 ± 0.0019	0.0195 ± 0.0038
40-60	0.0163 ± 0.0015	0.0154 ± 0.0016
60-80	0.0140 ± 0.0013	0.0140 ± 0.0014
80-100	0.0117 ± 0.0012	0.0110 ± 0.0011
......	....	....
260-280	0.0078 ± 0.0008	0.0078 ± 0.0009
......	....	....
540-560	0.0055 ± 0.0005	0.0054 ± 0.0009

The extrapolated curve of w_p or w_D as function of R_r leads to the relativistic limit of $w = 3.0$ KeV/grain.

Besides, for the electron tracks with $R_r \leq 20.0 \; \mu m$ it was determined that $w_e = (0.0433 \pm 0.0042)$ MeV/grain. Actually this result was directly obtained with a radioactive standard source of $^{210}B_{183}$.

Table II shows the results of the measurements which were carried out on the last 20 μm of residual range. These short linear residual ranges were chosen to test the reliability of the method. The tracks were selected by a non systematic scanning. For any of these nuclidi, $\mathcal{X} = 1.540605$ MeV.

The experimental value of ΔE was determined by the number of

TABLE II

Atomic Nuclide	E(experimental) (MeV)	E(theor.) (MeV)	d (um)	$\bar{Z}_{eff}$	Isotopic mass ratio.
$^1H_1$	(calibration nuclide)	1.540605	0.700 ± 0.023	1.0	$^2H_1/^1H_1$ =2.00082 ±0.50701
$^2H_1$	2.07880 ± 0.22757	2.078434	1.000 ± 0.080	1.0	
$^4He_2$	5.4400 ± 0.6100	5.467274	1.217 ± 0.023	1.8	$^4He_2/^3He_2$= 1.34253 ± 0.50812
$^3He_2$	4.7900 ± 0.5700	4.822833	1.142 ± 0.026	1.8	
$^7Li_3$	6.67546± 0.52357	6.962469	1.343 ± 0.021	1.8	$^8Li_3/^7Li_3$ = 1.12271 ± 0.14071
$^8Li_3$	7.01512± 0.52336	7.375913	1.377 ± 0.020	1.8	
$^{12}C_6$	9.6377 ± 1.9482	9.905302	1.614 ± 0.030	2.0	$^{13}C_6/^{12}C_6$ = 1.18083 ± 0.1100
$^{13}C_6$	10.3589 ± 2.2643	10.253803	1.6733 ± 0.048	2.0	

The following number of nuclidi are shown in this Table ; 11, ^1H; 6,^2H; 5,^4He; 3,^3He; 7, ^7Li; 5, ^8Li; 7,^{12}C and 7,^{13}C.

the inner silver developed grains times the value of w_p corresponding to R_T = 20.0 μm (Table I). The theoretical[p] one, by formula (2). All the tracks were also identified by the classical method.Once knowing the experimental value of E , Z_{eff} (average value in 20 μm) and the ratio between isotopic masses were deduced.

Table III indicates the results corresponding to a part of the 29 nuclidi which were inside of 37 central plates of a package of emulsions which flew at an average altitude of 4.5 g/cm² during 16 hours, in 19 to 20 of July of 1958 over Minneapolis, Minn.; the 200 plates of Ilford G-5 emulsions of 15x15 cm x 600 μm each,were kindly afforded to the author of the present paper by the late Professor of The University of Chicago, Dr. Marcel Schein.

The above mentioned 29 nuclear tracks, which had $Z \gtrsim 3$ and stopped inside the emulsions, entered at 7 mm from the superior edge of each sheet and were distributed as it follows:

^6Li	^7Be	^{10}Be	^{10}B	^{11}B	^{11}C	^{12}C	^{13}C	^{13}N	^{14}N
1	3	1	1	1	3	6	1	2	5

$$^{18}O_1 - {}^{21}Ne_1 - {}^{24}Mg_1 - {}^{27}Al_1 - {}^{35}Cl_1$$

TABLE III

$z^{1.136} A^{0.432}$ (exp.)	$z^{1.136} A^{0.432}$ (theo.)	Assigned Nuclide	w (MeV/grain)	R_r
7.361951±0.730232	7.553897	$^{9}Li_3$	0.0081	205.28
11.640685±1.316993	11.194959	^{7}Be	0.0066	348.51
13.619709±1.540894	13.0599089	^{10}Be	0.0077	230.02
16.687503±1.887975	16.827900	^{10}B	0.0071	283.19
26.877412±2.994446	27.621999	^{13}B	0.0062	422.50
27.933732±3.160341	28.520602	^{14}N	0.0063	374.98
20.847880±2.358668	21.570562	^{11}C	0.0063	372.12
22.305500±1.596050	22.396808	^{12}C	0.0056	497.80
22.953260±2.596865	23.184799	^{13}C	0.0054	550.20
50.933117±5.762424	50.956400	^{21}Ne	0.0056	554.87
67.491854±7.635832	66.405056	^{24}Mg	0.0055	540.74
117.16624±13.25585	116.098704	^{35}Cl	0.0055	546.63

3.- Conclusions. Taking into account that the identification of the above measured nuclidi was done by determining the inner granulometric density in only two successive cells of 23.44 μm each and which were located at a residual range R_r (see Table III), to improve the precision of the determination of Z and A it is suggested that the measurements of each track have at least to observe the following steps:

(a) Start the determination of the inner granulometric density, in 2 or 3 consecutive cells, from the stopping point of the track. This zone has a very small number of standard J-rays.

(b) Measurements of that granulometric density have to be carried out in several consecutive cells which should permit to determine the transition from Z_{eff} to Z.

(c) Measurements of several cells have to be done in the track segment in which the value of $Z^{1.136} A^{0.432}$ should remain as a constant one inside its experimental errors.

In (b) and (c) it is necessary to add the energy of the standard J -rays (of 2 or more grains) which in our case resulted at a rate of 0.0423 MeV/grain.

To obtain the above given 29 nuclidi, the author of this paper has observed only point (c). Complementary measurements on this group of particles by taking into account points (a) and (b) shall improve the spectral distribution of A and Z. Besides, with this criterion measurements will be carried out on another group of 60 stopping nuclidi belonging to the same package of nuclear emulsions.

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OBSERVATIONS OF ULTRAHEAVY COSMIC RAY PARTICLES
AT 10 GV CUTOFF RIGIDITY

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ABSTRACT
Ultraheavy cosmic ray particles with $Z>45$ and Fe were observed in two balloon flights at a mean geomagnetic cutoff rigidity of 10 GV. Fluxes of these particles at the top of the atmosphere are presented. A ratio of $(Z>45)/(Fe)$ is compared with other experimental results. The ratio decreases with increasing energy in the energy range from 1 to 10 GeV/amu. A possibility is presented to explain the variation of the ratio with energy.

1. Introduction. Early observations of ultraheavy cosmic ray particles (UH) were mainly made by balloon-borne track detectors at high geomagnetic latitude regions[1,2,3]. In the observations, UH were collected enough to obtain approximate chemical compositions. Recently, more precise measurements on the abundances of UH were achieved by using electronic detector systems on board the Ariel 6[4] and the HEAO-3[5] satellites and a picture of the origin of the cosmic rays based on the early results was suffered significant alteration. However, to determine energy spectra of UH, more data are required.

Plastic detectors are useful instruments for measurements on the fluxes of charge groups of UH, since a large area array can be easily constructed. For observations of relativistic particles, in particular we can realize an extremely large area array, because nuclear charges of such particles can be determined with singly layered plastic sheets.

In our observations at a mean cutoff rigidity of 10 GV, no cosmic ray particles of $E \leq 2$ GeV/amu can enter from any direction.

2. Experimental Configuration. Two arrays A_1 and A_2 were launched from Sanriku Balloon Center at a mean cutoff rigidity of 10 GV in 1976 and in 1982, respectively. A total collecting power of A_1 expanded vertically with an area of 50.4 m^2 was 846.2 $m^2 \cdot hr$ at a mean residual atmosphere of 11.2 g/cm^2 and that of A_2 expanded horizontally with an area of 28.8 m^2 was 238.5 $m^2 \cdot hr$ at a mean residual atmosphere of 7.7 g/cm^2. Each array was composed of plastic detector stacks of 40 cm $\times$ 50 cm in area consisting of three CN, two CTA and two or one PC sheets. To measure the flux of Fe, several small size stacks of emulsion and of CR-39 were also included in A_1 and A_2, respectively. In both observations, two CN sheets in each stack were used to detect tracks by ammonia vapour method and the others to determine the charges.

In the CN sheets, 9 tracks produced by UH with $Z \geq 40$ were found; 5 in A_1 and 4 in A_2.

For calibrations, CN and CTA stacks were exposed to ^{40}Ar beams of 400 MeV/amu at the Bevalac. The charge resolutions were characterized by standard deviations of about 3 and 5 charge units at $Z \sim 50$ for the CN and the CTA, respectively.

3. Data Analysis. For the emulsion, δ-ray counting method were applied. On the other hand for the CR-39, using growth rate (V_t) data of etch pits, we first prepared scatter plots of normalized etch rates $(V_t/V_g -1)$ vs. $\sin \delta$, where V_g and δ are a bulk etch rate of the CR-39 and a dip angle of a track, respectively. From these analyses, frequency distributions of δ-ray densities along tracks in the emulsion and of the normalized etch rates projected on the line of $\sin \delta =1$ were obtained. Compared with well-known chemical composition of

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cosmic rays with $Z \leq 26$, the frequency distributions were converted into charge distributions. One of the results obtained from the CR-39's data is shown in Fig. 1. No correction was made for geometric factor which varies with atomic number. The observed charge resolutions were characterized by standard deviations of 0.55 and 0.34 charge units at Fe for the emulsion and the CR-39, respectively.

The data of track etch rates in the CN and the CTA were used to determine nuclear charges of UH. No track was recorded in the PC sheets which are insensitive to relativistic particles with $Z \leq 70$. The track etch rate data and the charges assigned to all events are shown in table 1. In CTA, there is an apparent difference in sensitivity between front and back surfaces.

Fig. 1 Chemical composition of the particles found in the CR-39 of 100 cm^2.

Taking account of nuclear spallations in the overlaying atmosphere, we obtained the fluxes of Fe and UH at the top of the atmosphere. For the calculations of the nuclear spallations, we used Hagen's formula(6) for the total cross sections and extrapolations of Silberberg and Tsao formulae(7) for the partial ones. Scanning efficiency for lighter particles being insufficient, we restricted our attention to the particles with $Z > 45$.

TABLE 1
The Track Etch Rates and The Charges Assigned to All Events

	Event No.	CN Etch Rate ($\mu m/hr$)	Z	CTA (Front) Etch Rate ($\mu m/hr$)	Z	CTA (Back) Etch Rate ($\mu m/hr$)	Z
A₁	23	27.4	46	—	—	—	—
	36	27.9	47	2.35	53	1.38	52
	62	29.5	47	2.87	52	1.83	54
	208	16.9	42	—	—	—	—
	235	12.0	40	—	—	—	—
A₂	1-19	46.1	55	2.46	54	1.43	52
	3-23	69.3	67	—	—	26.0	75
	3-27	53.1	58	2.00	52	2.57	54
	3-34	69.1	67	4.58	60	8.92	60

4. Results and Discussion. The fluxes of both Fe and UH obtained from two observations were consistent with each other. The combined values of the fluxes were as follows;

$$0.11 \pm 0.01 \quad \text{particles/}m^2 \cdot sr \cdot sec \quad \text{for Fe and}$$

$$(3.9 \pm 1.5) \times 10^{-6} \quad \text{particles/}m^2 \cdot sr \cdot sec \quad \text{for } Z > 45.$$

As a flux ratio of $(Z > 45)/(Fe)$, the following value was obtained;

$$(3.5 \pm 1.6) \times 10^{-5} \quad \text{for } R > 10 \text{ GV.}$$

This value is shown in Fig. 2 with other experimental results. The datum of the

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HEAO-3 was infered from a charge composition summarized by Mewaldt[8]. The result of Blanford et al. [3] was that obtained from a balloon observation by using plastic detectors at a cutoff energy of 1 GeV/amu. Assuming a power law spectrum with a index of 2.6, we plotted the ratios deduced from integral fluxes at mean energies in the figure.

It is clear in the figure that the ratio decreases with increasing energy in the energy range from 1 to 10 GeV/amu. The decrease means that the energy spectrum of UH with Z>45 is steeper than that of Fe. The difference in the energy spectra is to be ascribed to the effects of cosmic ray propagation in the Galaxy, if indices of injection energy spectra of all particles are assumed to be the same.

Fig. 2 Observed abundances of the particles with Z>45 relative to Fe (Fe=10^6).

To examine the effects, propagation calculations based on a exponential path length distribution were made[9]. In the calculations, we used

(1) Cameron's [10] solar system abundances for source composition,

(2) Silberberg and Tsao[11,12] semiempirical formulae with the modifications of 1977[13], 1979[14] and 1983[15], for the spallation cross-sections and

(3) the semiempirical formulae by Silberberg et al. [16] for the total inelastic cross-sectios,

and included the effects of

(1) first ionization potential enhancement and

(2) solar modulation with a deceleration parameter of 500 MV.

The effects of the ionization losses were neglected, since they are not so important in the energy range of interest.

All injection spectra were taken to be proportional to $W^{-2.3}$, where W is total energy per nucleon.

We considered collisions up to nine times and treated individually 323 isotopes from Nb to Bi, which are either stable, long lived or decayable exclusively by electron capture, and about 800 short lived isotopes produced by collisions and subsequent radio active decays.

The following energy dependent escape mean free path λ_e was determined to explain the experimental results for the ratio of (sub-Fe)/(Fe) in the energy range from 0.6 to 30 GeV/amu;

Fig. 3 The variation with energy of the (sub-Fe)/(Fe) ratio.

$$\lambda_e = \begin{cases} 8.0 & \text{g/cm}^2 & \text{for } E \leq 2 \text{ GeV/amu,} \\ 8.0\,(E/2) & \text{g/cm}^2 & \text{for } E > 2 \text{ GeV/amu.} \end{cases}$$

Figure 3 shows the variation with energy of the (sub-Fe)/(Fe) ratios. The predicted curve is consistent with the experimental results over the above range of energy.

The result of the calculation is presented for the (Z>45)/(Fe) ratio on

Fig. 4 and compared with
the experimental data.
The curve reproduces
well the variation of
the observed ratios.
An increase around
800 MeV/amu is due main-
ly to similar increases
in the spallation cross-
sections of heavy nuclei
around 1 GeV/amu. An in-
crease in the partial
cross-sections in the
mass range of $10 < \Delta Z < 40$
at 1 GeV was shown in
the measurements of
Kaufman and Steinberg
(17) on the spallation
of ^{197}Au. The data ob-
tained from the measure-
ments were incorporated

Fig. 4 The variation of the predicted ratio of
$(Z > 45)/(Fe)$ compared with the observed data.

into the semiempilical formulae by Tsao et al. (15).

A possible interpretation of the variation with energy of the $(Z > 45)/(Fe)$
ratio shown by the propagation calculation is as follows.

The ratio of (secondaries with $Z > 45$)/(Fe) increases significantly around
1 GeV/amu because it depends strongly on the spallation cross-sections. The al-
ternative ratio of (primaries with $Z > 45$)/(Fe) depends on the attenuation and the
escape mean free paths and varies with a simple manner with energy. And the cal-
culations showed that the secondaries are dominant in UH at 1 GeV/amu. There-
fore, the $(Z > 45)/(Fe)$ ratio in the interstellar space increases at 1 GeV/amu.
The effects of the solar modulation shift the increase to lower energy side.

Above 3 GeV/amu, where the spallation cross-sections change little with en-
ergy, the (primaries)/(Fe) ratio increases with increasing energy, while the
(secondaries)/(Fe) ratio continues decreasing, because the interstellar matter
traversed by cosmic rays decreases with increasing energy. As a result, the
$(Z > 45)/(Fe)$ ratio decreases gradually with increasing energy at least up to
~ 10 GeV/amu.

The increase around 800 MeV/amu dominates the variation of the ratio of
$(Z > 45)/(Fe)$. It results mainly from the increases in the spallation cross-
sections at 1 GeV/amu. This emphasizes the importance of another measurements of
the spallation cross-sections.

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ARIEL VI MEASUREMENTS OF ULTRA-HEAVY COSMIC RAY FLUXES. IN THE REGION 34 ≤ Z ≤ 48

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1. Introduction. The Ariel VI satellite was launched by NASA on a Scout rocket on 3rd June 1979 from Wallops Island, Virginia, USA, into a near-circular 625 km orbit inclined at 55°. It carried a spherical cosmic ray detector designed by a group from Bristol University. The salient features of this detector are shown in Fig. 1.
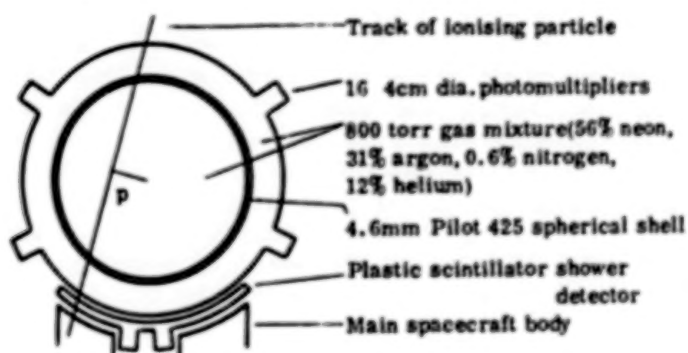
Fig. 1 Schematic cross-section of Ariel VI Cosmic ray detector

A spherical aluminium vessel of diameter 75 cm contains a gas scintillation mixture and a thin spherical shell of Pilot 425 plastic, and forms a single optical cavity viewed by 16 photomultipliers. Particle tracks through the detector may be characterised by their impact para-meter p and by whether or not they pass through the cup of plastic scintillator placed between the sphere and the spacecraft body (referred to below as the Anti-Coincidence Detector or ACD). Individual particle charges are determined by separately measuring the gas scintillation and the Cerenkov emission from the plastic shell. This is possible because of the quite different distribution in time of these emissions. See also (1).

The last data from Ariel VI was received in February 1982, but spacecraft power supply problems had restricted data collection to only 427 of the days in orbit, with actual experiment live-time equivalent to 352 complete days at 100% efficiency.

2. Data Selection. Results from a first analysis of part of the Ariel VI data set have already been reported (2). The present analysis covers all available high charge data collected by Ariel VI. It includes improvements to the cut-off map used to apply cut-off labels to individual events and new event timings which allow for imperfections in the spacecraft clock by using measured cosmic ray fluxes as clock calibrations. Event timing, and the subsequent allocation of an inferred local vertical cut-off to an individual event, is important for the Ariel VI data analysis because a small number of low energy iron nuclei, which can stop in the detector at

high impact parameters, can simulate higher charges up to a limit of apparent charge 47. Hence, for abundance measurements in the charge region $34 \leq Z \leq 48$, data can only be accepted from those regions where the earth's magnetic field excludes such low energy iron nuclei. This is empirically determined to be for vertical cut-offs greater than 3.4 GV.

Finally, with the improved statistics from the complete mission, it is seen that events which produce a signal in the ACD (hits) have a cut-off distribution indicative of pollution from electron showers to the highest charges, though hardly statistically significant for $Z \geq 70$. The hit spectrum also shows evidence of additional fragmentation due to passage through the body of the spacecraft. Consequently these ACD hits require separate analysis and are not included in the results quoted in this paper or in the companion paper OG4.4-4.

3. Results. Fig. 2 shows the distribution of accepted data for this charge region. Numbers given are actual numbers of detected events, with two provisos: i) a correction has been made for the exponential tail associated with the relativistic rise in energy loss for charges 30,31,32 using measured abundances from HEAO3-C2 (3); this affects the first five bins: ii) some events in the lower part of this charge region have been collected as events of second highest priority (1), at lower efficiency, and in this case scaling has been made event by event to an equivalent 100% efficiency; this effect has become small by bin 8 onwards.
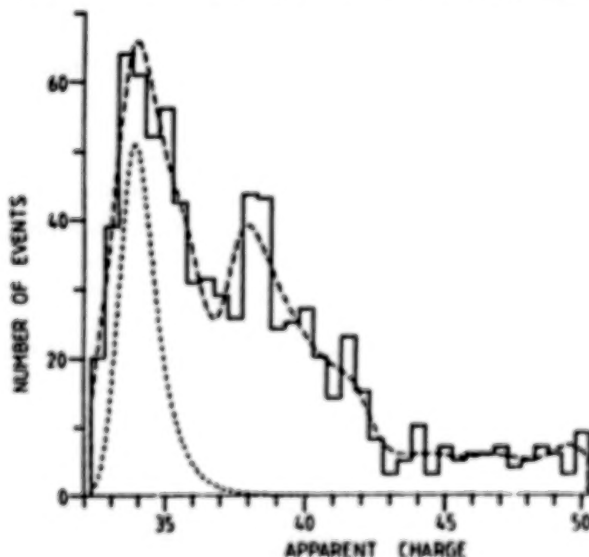
Fig. 2 Distribution of accepted data for determination of $33 \leq Z \leq 48$ abundances.Dotted insert shows distribution of $_{34}$Se content from Table 1.

During data re-analysis small improvements have been made to charge allocation as a function of gain setting and an energy dependent non-Z^2 correction has been applied to all data. This is discussed further in OG4.4-4. Its effects are in any case small for $Z \leq 48$.

In order to allot events to individual charge species the effects of the resolution function of the experiment must be removed from the data in a deconvolution procedure. The resolution function is well determined

OG4.4-3

Table 1   Elemental Abundances for $33 \leq z \leq 48$

| | Ariel VI | | | Comparison Data | | |
z	Deconvolved Numbers	Corrected to outside expt	Charge pairs	HEA03-C3	SS + FIPD propagations Brewster et al.	Letaw et al.
26	3.46×10^6	10^6	10^6		10^6	10^6
33	(81 ± 21)	(21 ± 6)	72 ± 5	$[9]<19$	11	68
34	180 ± 29	51 ± 8		$43 {+10 \atop -6}$	55	
35	84 ± 25	24 ± 7	43 ± 4	$[7]<14$	10	31
36	71 ± 23	19 ± 6		$23 {+8 \atop -5}$	24	
37	22 ± 30	6 ± 5	38 ± 4	$[9]<16$	20	47
38	110 ± 24	32 ± 7		$35 {+10 \atop -6}$	46	
39	54 ± 25	14 ± 7	26 ± 4	$[5]<12$	8	24
40	42 ± 20	12 ± 6		$13 {+5 \atop -4}$	16	
41	33 ± 22	9 ± 6	19 ± 4	$[3]<6$	2.5	10
42	35 ± 13	10 ± 4		8 ± 2	6.5	
43	0		3 ± 2			7.0
44	12 ± 8					
45	13 ± 14		6 ± 2			6.0
46	9 ± 12					
47	14 ± 13		6 ± 2			4.9
48	9 ± 13					

for $_{26}$Fe and is found to fit well to a Gaussian part and an exponential tail to high charge (2). In addition the shapes of the abundance peaks at $_{12}$Mg, $_{14}$Si and $_{20}$Ca allow the variance of the Gaussian to be separated into a Poisson part and a part varying as Z^2. A resolution function may then be constructed for any higher charge by extrapolation. The resolution function for $_{34}$Se is shown as a dotted insert in Fig. 2. Using these functions the observed data may be deconvolved into a best-fit set of abundances, giving the numbers shown in column 2 of Table 1. These numbers yield the curve shown in Fig. 2 when operated on by the appropriate resolution functions. The fit is seen to be reasonably good, though the Z = 38 peak appears offset. The decrease in numbers of detected events around Z = 43 is too steep for the measured resolution function of the experiment. This fluctuation results in a best-fit abundance for Z = 43 which is approximately 1½ s.d. below zero. This value was set at zero and not varied in subsequent fitting procedures.

4. Discussion.   The limited charge resolution achieved by the Ariel VI detector reveals only one clear charge peak in this region, at Z = 38, and only one odd charge, Z = 35, is strictly necessary to obtain a good fit to the data. Nevertheless the best-fit abundances in column 3, which have been corrected for fragmentation in the experiment, form the most convenient comparison with other work. The errors shown are the excur-

sions needed in a given abundance to produce a change of one unit of χ^2, the two neighbouring abundances being adjusted to keep the total area constant. They may be regarded as approximations to 1 s.d. errors for individual charges. With this procedure, fluctuations are strongly anti--correlated between neighbouring abundances and a significant decrease in the errors results when abundances for charge pairs are constructed as in column 4.

The best-fit values and upper limits presented by the HEAO3-C3 group at Bangalore (4) are shown in column 5, and agreement between the two experiments for individual charges is seen to be uniformly good, though the integrated total is rather higher for the Ariel VI data. Columns 6 and 7 of the table quote results from two propagations of Cameron (1982) solar system abundances (5) through about 6 gmcm^{-2} of ISM with slightly different assumed First Ionisation Potential Dependence (Brewster et al. (6) and Letaw et al. (7)). Agreement between observed cosmic ray abundances and propagated SS is seen to be reasonably good in this area, with the FIPD of ref. (7), which saturates at potentials less than 7 eV, producing better agreement around charge 38.

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OG4.4-4

ARIEL VI MEASUREMENTS OF ULTRA-HEAVY COSMIC RAY FLUXES
IN THE REGION Z ≥ 48

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1. Introduction.   The Bristol cosmic ray detector on the Ariel VI sat-
ellite is described briefly in OG4.4-3 and more fully in Ref.(1). The
data for charges Z ≥ 48 discussed in this paper were obtained with the
same data selection and analysis criteria set out in OG4.4-3, except that,
for this high charge region, pollution from slowing iron nuclei is not
possible and data collected at all vertical cut-offs may be used.

     For this re-analysis of the Ariel VI data, the contribution of
non-Z^2 effects to the restricted energy loss and to Cerenkov radiation in
the Bristol sphere has been evaluated using the Mott cross section ratios
tabulated in (2) and the non-relativistic Bloch correction given clearly
in (3). Results obtained were similar in form to those derived for
HEAO3 by Derrickson et al. (4) but with maximum deviations ~10% rather
than 15% for the Mott term, corresponding to a thinner detector. Because
of the large uncertainties in the parameters involved, no relativistic
Bloch term was included; in any case Waddington et al.(5) found no sig-
nificant deviation from Mott plus non-relativistic Bloch in their exper-
imental work. In addition the experiments of Garrard et al. (6) on the
HEAO detector make the application of a correction to the Cerenkov res-
ponse of doubtful justification and none has been applied in this analy-
sis. An energy dependent correction was made using an effective energy
calculated from the vertical cut-off for a given event. The maximum
value of this correction was about 0.6% in Z for low cut-offs, declining
to ~ zero by 10 GV.
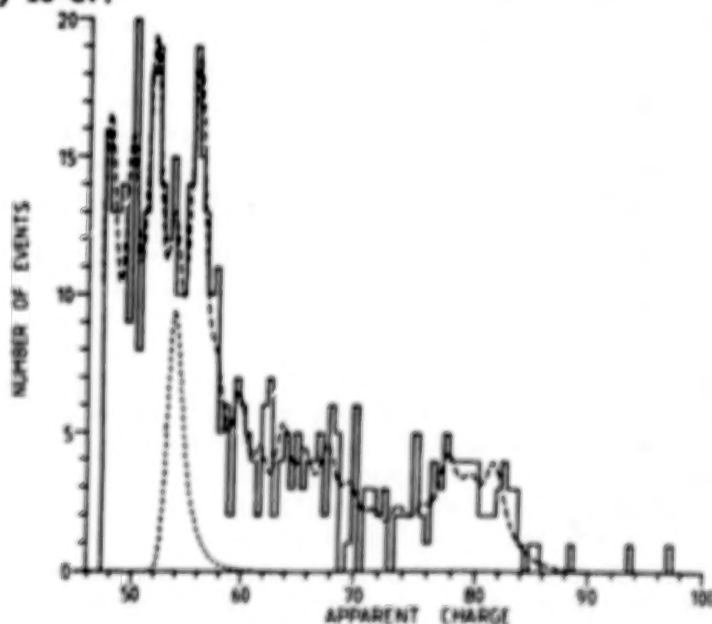
Fig. 1 Distribution of accepted data for determination of Z ≥ 48 abun-
        dances. Dotted insert shows distribution of $_{54}Xe$ content (Table 1)

2. Results.   Fig.1 shows the distribution of data for all charges $Z \geq 48$. These events were accompanied by 8.68×10^6 $_{26}$Fe nuclei. In this distribution all events were collected at the highest priority and numbers given are actual numbers of detected events. The resolution function for $_{54}$Xe is shown as a dotted insert and clearly resolved peaks are seen for $_{52}$Te and $_{56}$Ba. A similar procedure of deconvolution was followed for this data to that described in OG4.4-3, but with a resolution function supplied only for each even charge, odd abundances being set to zero. The derived numbers are shown in column 2 of Table 1. The peaks at $_{52}$Te and $_{56}$Ba in Fig.1 are seen to be consistent with the predicted resolution, as is the precipitate fall from $Z = 56$ to $Z = 60$.
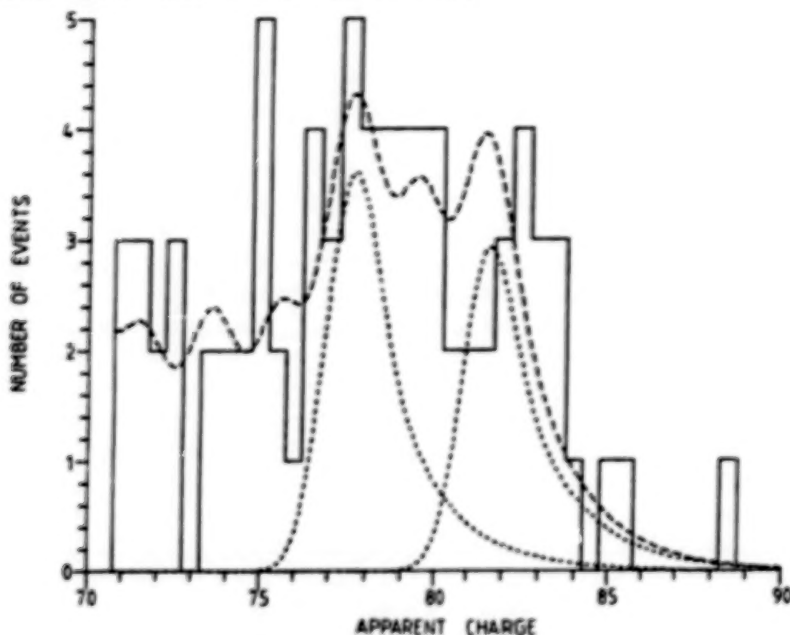
Fig. 2 Detail of the highest charges from Fig. 1. Dotted inserts show
distributions for $_{78}$Pt and $_{82}$Pb content from Table 1.

Fig. 2 shows an expanded version of Fig. 1 for the $_{78}$Pt - $_{82}$Pb region alone. The inserted dotted lines show the predicted distribution in apparent charge of the $_{78}$Pt and $_{82}$Pb abundances obtained from the deconvolution. The tail of the $_{82}$Pb distribution is seen to extend out to $Z_{app} \sim 88$ but only 0.1 event with $Z_{app} \gtrsim 90$ is predicted. Thus events with $84 \leq Z_{app} \leq 86$ are mainly the high energy $_{82}$Pb nuclei which produce the exponential tail. Three events with $Z \geq 88$ were actually seen in this exposure, with Z_{app} 88.5, 93.5 and 97.0 following the non-Z^2 correction discussed in section 1.

3. Discussion.   Data collection on Ariel VI allowed $_{26}$Fe events to be recorded whenever the experiment was operational, with a continuously-measured efficiency. Consequently the normalisation of the data to abundances relative to $_{26}$Fe $= 10^6$ is straightforward. Column 3 of Table 1 shows normalised abundances, with a small correction added to allow for fragmentation in the material of the experiment, and these values are plotted as data points in Fig. 3 (together with the numbers from $34 < Z < 46$ for completeness). The numbers are compared with a recent propagation of Letaw et al. (7) which used solar system abundances modified by a first ionisation potential dependence, an exponential pathlength

distribution with characteristic length 6 gcm^{-2} of ISM and a propagation energy of 5 GeV/nucleon (histogram in Fig.3 and column 5 of Table 1). It is seen that the deconvolved Ariel VI abundances retain the over-abundance throughout the region $60 \leq Z < 80$ which has already been discussed (e.g. 7,8). The Ariel VI to Letaw et al. propagation ratio for $60 \leq Z \leq 82$ is 1.87 ± 0.14 based on 170 detected events. Letaw et al. attempted to go some way towards explaining this over-abundance by suggesting that propagation may take place mainly at a lower energy (~ 1 GeV/nucleon), where spallation into the $60 < Z \leq 74$ region is more favourable, but much of the discrepancy remains, the ratio being reduced only to 1.51 ± 0.12, suggesting an enhanced primary component in this region. The Letaw et al. propagations also produce consistently more $_{50}$Sn than was seen in the Ariel VI data, and in that from HEAO3-C3 (9), which is shown for the charge region $50 \leq Z \leq 58$ in column 4 of Table 1 for comparison. Agreement between the two experiments is quite good in this region, but with a divergence of ~ 3 s.d. at $_{52}$Te where a separated peak is seen in the Ariel VI data.

For the highest charges, Binns et al. (10) quote a value for the abundance ratio $\dfrac{Z \geq 81}{74 \leq Z \leq 80}$ of 0.26 ± 0.08. Ignoring the three actinides our value for this ratio is 0.35 ± 0.12, higher, but not inconsistent with the HEAO value, and consistent with either the SS with no FIP fractionation or pure r-process with FIP fractionation values quoted in (10). Although the $_{82}$Pb abundance seen in the Ariel VI data may not share the $60 \leq Z < 80$ over-abundance compared to propagated solar-system, it is not found to be depleted, being very close to the predicted abundance from the propagation.

Finally, three actinide candidates were seen in the Ariel VI exposure, compared to an expectation of 0.5 from the Brewster et al. propagation (11), a possible enhancement.

Fig. 3 Cosmic ray abundances normalised to $_{26}$Fe $= 10^6$. Data points are deconvolved abundances from Ariel VI corrected for fragmentation within the experiment. The histogram shows the Letaw et al. propagation of solar system material (7) referred to in the text.
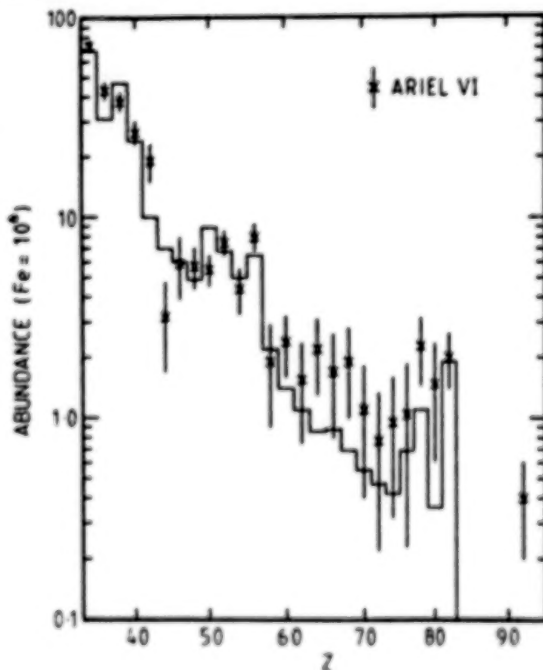
Table 1   Elemental Abundances for $Z \geq 48$

	Ariel VI			
Z	Deconvolved Numbers	Corrected to outside expt.	HEAO3-C3	SS + FIPD Propagation, Letaw et al.
26	8.68×10^6	10^6	10^6	10^6
48	54 ± 12	5.7 ± 1.3		4.9
50	52 ± 9	5.5 ± 1.0	5.7 ± 1.3	8.9
52	68 ± 9	7.5 ± 1.0	3.4 ± 1.0	6.8
54	39 ± 10	4.4 ± 1.1	3.5 ± 0.9	5.0
56	69 ± 10	8.0 ± 1.2	6.2 ± 1.0	6.5
58	17 ± 9	1.9 ± 1.0	2.8 ± 0.9	2.2
60	22 ± 7	2.4 ± 0.8		1.4
62	14 ± 7	1.6 ± 0.8		1.1
64	20 ± 8	2.2 ± 0.9		0.86
66	15 ± 8	1.7 ± 0.9		0.88
68	17 ± 8	1.9 ± 0.9		0.69
70	10 ± 6	1.1 ± 0.7		0.55
72	7 ± 5	0.8 ± 0.6		0.47
74	9 ± 6	0.9 ± 0.6		0.42
76	9 ± 7	1.0 ± 0.8		0.69
78	19 ± 7	2.3 ± 0.8		1.1
80	12 ± 7	1.5 ± 0.9		0.36
82	16 ± 5	2.0 ± 0.6		1.9
84	0			
≥ 88	3	0.4 ± 0.2		

4. **Acknowledgements.**   These are given in full in paper OG4.4-3.

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N 85 - 34038

Elemental Abundances of Cosmic Rays with Z > 33 as Measured on HEAO-3

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1. Introduction

The Heavy Nuclei Experiment on HEAO-3 (Binns et al., 1981) uses a combination of ion chambers and a Cerenkov counter. During analysis, each particle is assigned two parameters, Z_C and Z_I, proportional to the square roots of the Cerenkov and mean ionization signals respectively. Because the ionization signal is double valued, a unique assignment of particle charge, Z, is not possible in general. Our previous work (Binns et al., 1983, 1985, and Stone et al., 1983) has been limited to particles of either high rigidity or low energy, for which a unique charge assignment was possible, although those subsets contain less than 50% of the total number of particles observed. In this paper we discuss the use of the maximum likelihood technique to determine abundances for the complete data set from ~1.5 to ~80 GeV/amu.

Figure 1 shows the possible values of Z_C and Z_I for elements near iron, and indicates the substantial overlap between adjacent elements, even before smearing by the resolution function. In Figure 2, the curves of Figure 1 have been transformed using the variable Z_C/Z_I instead of Z_I. This transformation simplifies the following data analysis.

2. Analysis

Particles were selected from the full exposure, 580 days, and were required to have a good Cerenkov signal, at least one good ion chamber and a reliable trajectory. These particles were assigned an initial charge estimate, Z_{est}, and 1/40 of those with $Z_{est} > 19.5$ were saved, together with all the remaining particles with $Z_{est} > 30$. The selected particles were binned in a two dimensional histogram, with one axis being the logarithm of Z_C and the other being Z_C/Z_I. Figure 3 shows a contour plot of the region of this histogram near iron.
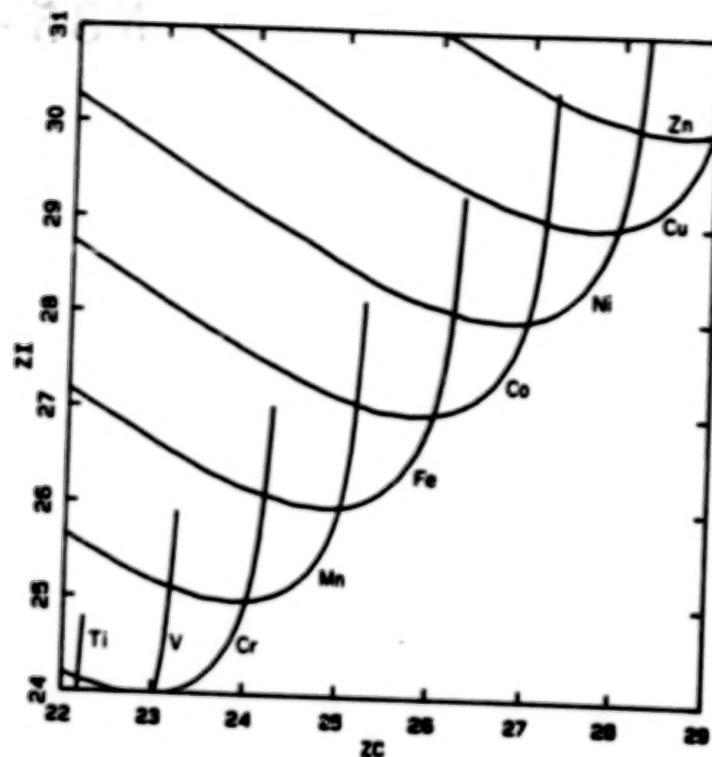
Figure 1. Curves of Z_I versus Z_C for the elements near iron.
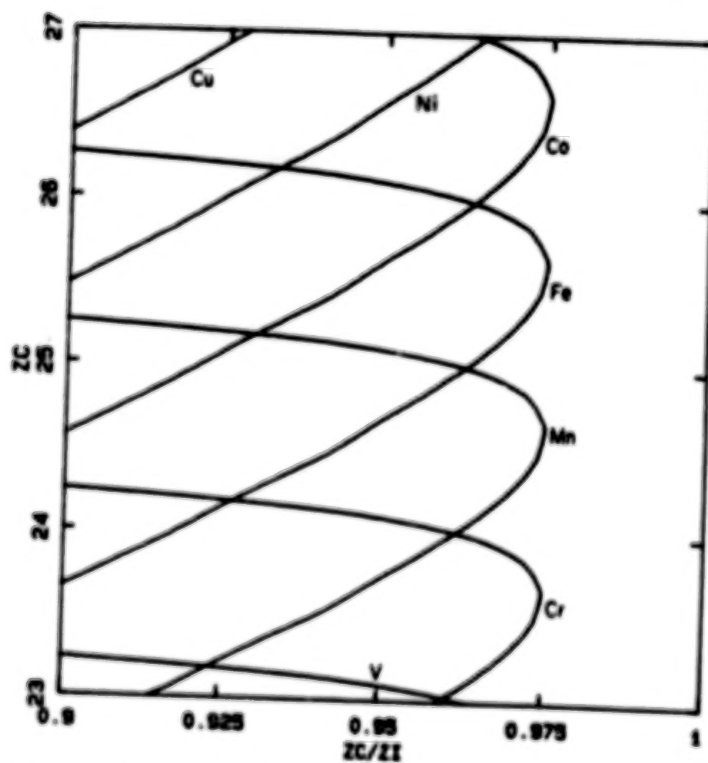
Figure 2. The curves of Figure 1, displayed in $(Z_I/Z_C, Z_C)$ space.
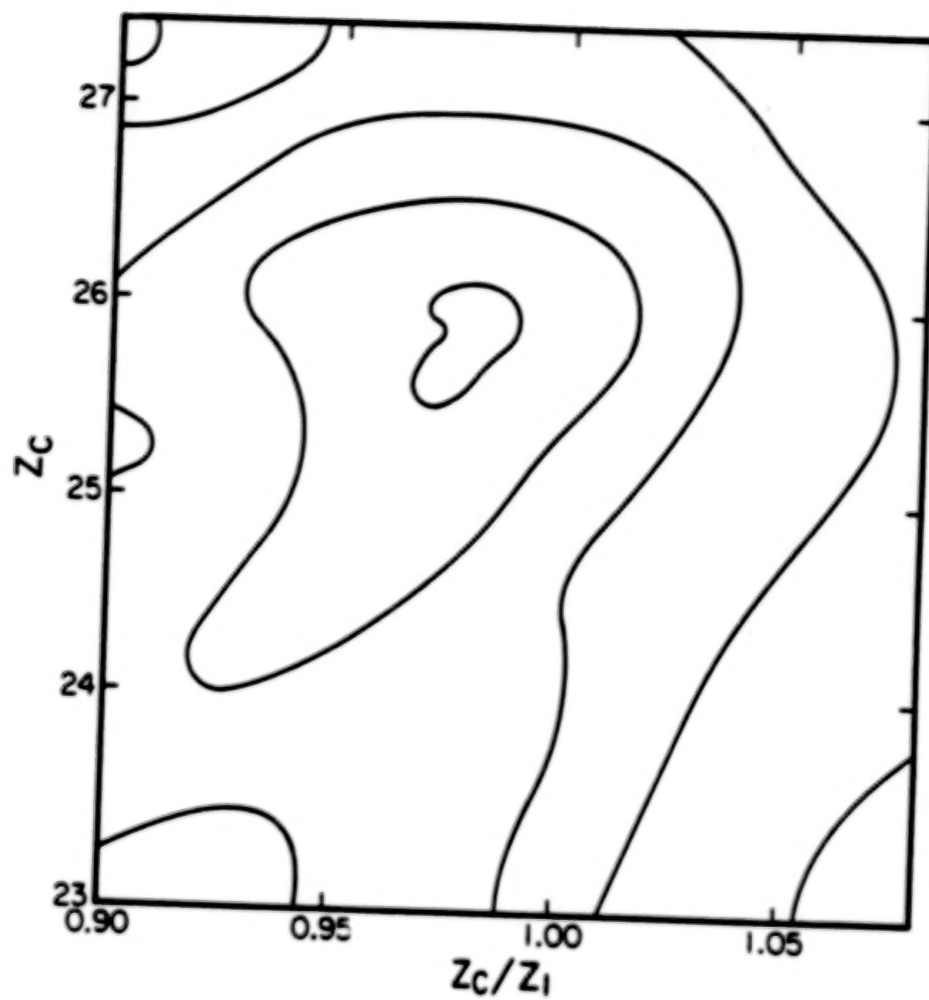
Figure 3. A contour plot of particle density in $(Z_1/Z_C, Z_C)$ space.

We have used the iron distribution as a reference distribution for the other elements, by scaling it according to the following criteria:

1) All elements are assumed to have the same energy spectrum, although it is known that the sub-iron secondary elements have steeper spectra (e.g. Jones et al., 1985, OG 4.1-8).

2) Energy independent scaling factors have been used.

3) The resolution of the instrument is a constant fraction of the signal.

4) Non-Z^2 corrections to the scaling laws for Z_C and Z_C/Z_I have been determined directly from the data.

Those elements contaminating the iron distribution have been approximately removed by scaling the contaminated distribution and subtracting according to an assumed set of abundances. The resulting "clean" iron distribution was smoothed and then scaled to the high Z elements, using cubic interpolation techniques.

The likelihood of a given set of abundances may be calculated using Poisson statistics, and maximized by iterating until all the first derivatives are zero, yielding the best fit. Results from the application of this method will be reported.

3. Acknowledgements

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ABUNDANCES OF 'SECONDARY' ELEMENTS AMONG THE ULTRA HEAVY COSMIC RAYS - RESULTS FROM HEAO-3

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1.Introduction.   This paper discusses observations of the abundances of elements of charge $62 \le Z \le 73$ in the cosmic radiation from the HEAO-3 Heavy Nuclei Experiment (HNE). These elements, having solar, and presumably source, abundances much less than the heavier Pt and Pb groups, are expected to be largely products of spallation. Thus they are indicators of the conditions prevailing during the propagation of cosmic rays. The abundances have changed from those reported previously (Klarmann et al., 1983) due to a different data selection (Binns et al., 1985). This resulted in better charge resolution and in a higher mean energy for the particles. All the particles we have included in this paper were required to have had a cutoff rigidity $R_c > 5$ GV. This allowed the charge determination to be based solely on the Cherenkov measurement. For a description of the detector see Binns et al., (1981).

2. Analysis.   The data selection in this paper is identical to that of Waddington et al., (1985, OG4.4-7). We have considered only the following physically significant groups of charges:

Name	Abbreviation	Range	Number observed
Lead and Platinum	PbPt	$74 \le Z \le 86$	52
Heavy secondary	HS	$70 \le Z \le 73$	10
Light secondary	LS	$62 \le Z \le 69$	34

Our discussion will be in terms of the ratios: HS/PbPt and LS/PbPt. In the table, column a) shows the results observed in the detector. The correction factor to outside the detector was derived by propagating eight different plausible theoretical abundances outside the detector through slabs of hydrogen approximating the distribution of aluminum traversed by the particles going into and through the detector. The change of the abundance ratios from outside the detector to inside was nearly independent of the original ratios and is given as a multiplicative correction factor in column b). The abundance outside the detector, column c) is the product of columns a) and b).

Ratio	HEAO Results			Ariel	HEAO/Ariel
	Inside Detector a)	Correction Factor b)	Outside Detector c)	Outside Detector d)	Outside Detector e)
HS/PbPt	0.19 ± 0.07	0.85 ± 0.02	0.16 ± 0.06	0.27 ± 0.07	0.59 ± 0.27
LS/PbPt	0.65 ± 0.14	0.87 ± 0.02	0.57 ± 0.12	0.88 ± 0.15	0.65 ± 0.18

Results from the Ariel-6 UH-nuclei detector which was exposed in a 55° inclination orbit (Fowler et al., 1984) are given in column d), while column e) gives the ratio of our HEAO results to those of Ariel. It is seen that for both ratios our result is about 60%

to 65% that of Ariel's. While these differences are only significant at a level of 1.5 to 2.0 standard deviations, it is unlikely that they are just statistical fluctuations. The data of Ariel extend to significantly lower energy than ours. At lower energies the abundance of secondaries is expected to be greater since both the interaction cross sections and the escape length are larger. We cannot tell yet whether this energy dependence is sufficient to explain the difference.

3. Comparison with Models.   The abundance ratios can be compared with predictions of various models. The source abundance used was either the solar system abundances of Anders and Ebihara (1982) (No FIP) or the same adjusted for an exponential dependence (Brewster et al., 1983a) on the first ionization potential (FIP). These were then propagated through the interstellar medium, assuming a leaky-box model, and using the revised code of Brewster et al., (1983a, 1985) with a rigidity dependent escape length (Ormes and Protheroe, 1983) that is 6.21 g/cm of hydrogen at 7 GV. The calculated values are for approximately the same mix of rigidities as the HEAO data. A different model of FIP fractionation (Cook et al., 1979; J. P. Meyer, 1981), in which the cosmic ray source is suppressed by a constant factor relative to solar abundances for elements with ionization potential above 9 eV, yields propagated abundance ratios which in, this charge range, are indistinguishable from those of the unfractionated source. Similarly, propagation of an r-process source abundance yielded ratios which in this charge region were close to those from a solar system source. Neither of the last two results is plotted in figure 1.
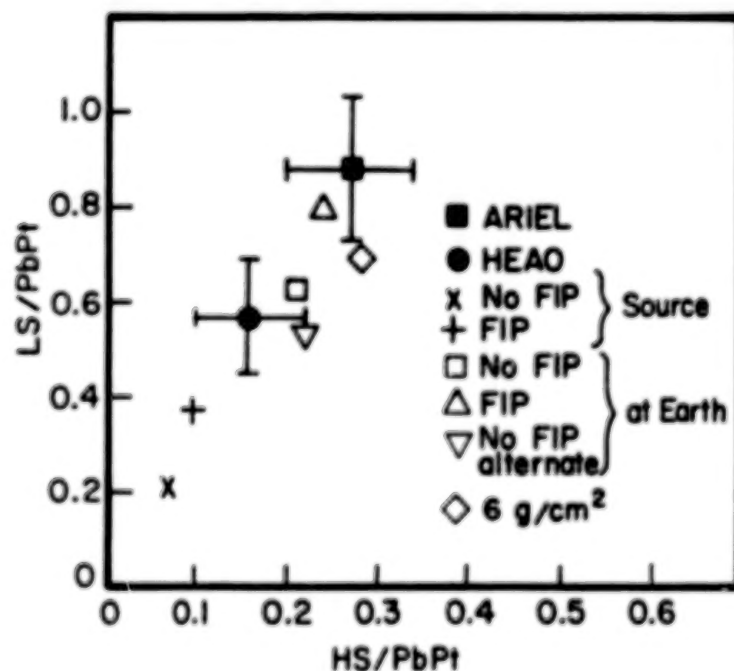
Figure 1: Comparison of the observed and predicted abundance ratios.

In the 'No FIP alternate' propagation an independent code was used (Margolis, 1983) to predict the abundance ratios after propagation through leaky boxes of various escape lengths. The results were then combined using the same rigidity dependent escape length distribution as above to yield the inverted triangle point in figure 1. With this rigidity dependent distribution the mean escape length encountered by the observed particles is ~3g/cm^2. This point, when compared to the other No FIP point, is an

indication of the variation possible in the propagation calculation. The point labeled '6 g/cm²' in figure 1 is the result of the same propagation through a leaky box with a single escape length of 6 g/cm² of hydrogen. The difference between this point and the 'alternate' point shows the dependence of the results on the escape-length distribution. In figure 1 experimental values are solid with error bars.

The dependence of the abundance ratio on propagation can also be demonstrated in a different way. Every point in figures 2 and 3 (Margolis and Blake, 1985) corresponds to the calculated ratio after propagation of a solar system source without FIP through hydrogen with a mean free path distribution rising linearly from zero to the desired 'truncation' then falling exponentially with the given 'escape length'(Margolis, 1983).
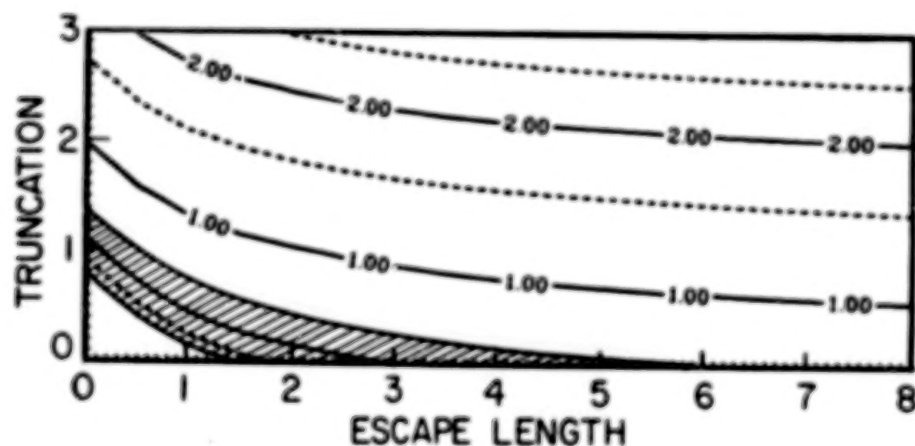
Figure 2: LS/PbPt
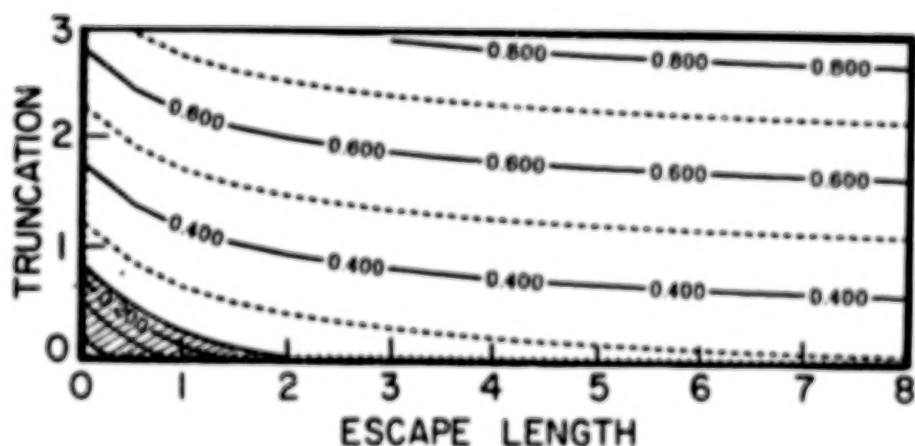
Figure 3: HS/PbPt

In contrast to the data in figure 1, these figures assume that all particles traverse the same path length distribution. Our results are represented by the cross-hatched region yielding possible combinations of escape length and truncation.

As expected the predictions in this charge region are nearly independent of escape-length since the interaction mean free path is so short. However the results do not agree with more than a minute amount of truncation of short path lengths. The fact that at zero truncation an escape length of $\sim 2g/cm^2$ is indicated seems to support the rigidity dependent escape length proposed by Ormes and Protheroe, (1983).

4. Discussion. Our observed values of the secondary ratios are in reasonable agreement with the prediction based on a model without FIP fractionation or with a step function FIP fractionation at the source; however, our observations are in distinct disagreement with the models that include exponential FIP fractionation. This is contrary to the conclusions found at lower charges (Binns et al., 1982, 1983) where observed abundances agreed better with those expected from a solar system source with FIP fractionation than without. Thus other representations of source fractionation may be involved.

Our results do fit the predictions obtained using the standard leaky box model in this energy range. The applicability of this model to lower energies requires further investigation.

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N85-34040 OG 4.4-8

CAPABILITIES OF THE LDEF-II HEAVY NUCLEI COLLECTOR

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1. Introduction. Less than about half a dozen relativistic actinide ($Z \gtrsim 90$) nuclei have been detected in space experiments--one on HEAO-3 [1], three on Ariel-6 [2] and possibly two on Skylab [3]. Our studies of long-term track fading suggest that partial fading of tracks produced early in the Skylab mission relative to those produced later may have smeared the charge scale and resulted in misidentification of some of the seven events originally reported as actinides. Events attributed to actinide nuclei using plastic track detectors and nuclear emulsions on balloon flights some years ago are now believed to be due mostly to spillover from the platinum and lead peaks, due to a shift in detector response with temperature during the day-night cycle of the balloon payload [4]. The HEAO-3 experiment, which had the best charge resolution to date for ultraheavy cosmic rays, resolved even-Z charge peaks up to $Z \sim 56$ and reported ~ 60 events with $Z \gtrsim 70$. Although their statistics and resolution were inadequate to resolve charges in this region, they were able to estimate the ratio of Pb-group to Pt-group nuclei to be $\sim 1\%$ based on one actinide event. Their data for all nuclei with $Z \gtrsim 30$ are consistent with a solar system source for the heavy cosmic rays, with the exception of a few elements such as Pb, which may be depleted in the cosmic rays. To take the next big step beyond HEAO-3, the Heavy Nuclei Collector (HNC), to be carried on an LDEF reflight, has the goals of greatly increased collecting power (>30 actinides) and charge resolution ($\sigma_Z \lesssim 0.25e$ for Z up to ~ 100), which will provide abundances of all the charges $40 \lesssim Z \lesssim 96$ and permit sensitive searches for hypothetical particles such as monopoles, superheavy elements, and quark nuggets.

2. Mission. After the currently orbiting LDEF is retrieved, it will carry 45 trays of plastic track detectors ($A\Omega \approx 100$ m^2 sr) into a 28.5 degree orbit for a 6-year exposure at $T < -10°$ C, after which it will be retrieved for analysis of the tracks. (At this writing, a 2.7-yr exposure in a 57° orbit, which would yield $\sim 10\%$ more actinides, has not been ruled out.)'

3. Design. To meet our goal of achieving a charge resolution $\sigma_Z < 0.25e$ at $Z = 92$, we used a number of novel features. Figure 1 is a cutaway sketch of the contents of one of the 45 trays, 41 of which are optimized for identification of nuclei with $Z \gtrsim 70$ and 4 of which are optimized for nuclei with $30 \lesssim Z \lesssim 70$. Detector response depends on temperature and oxygen pressure, and stability of the latent track against fading demands a low

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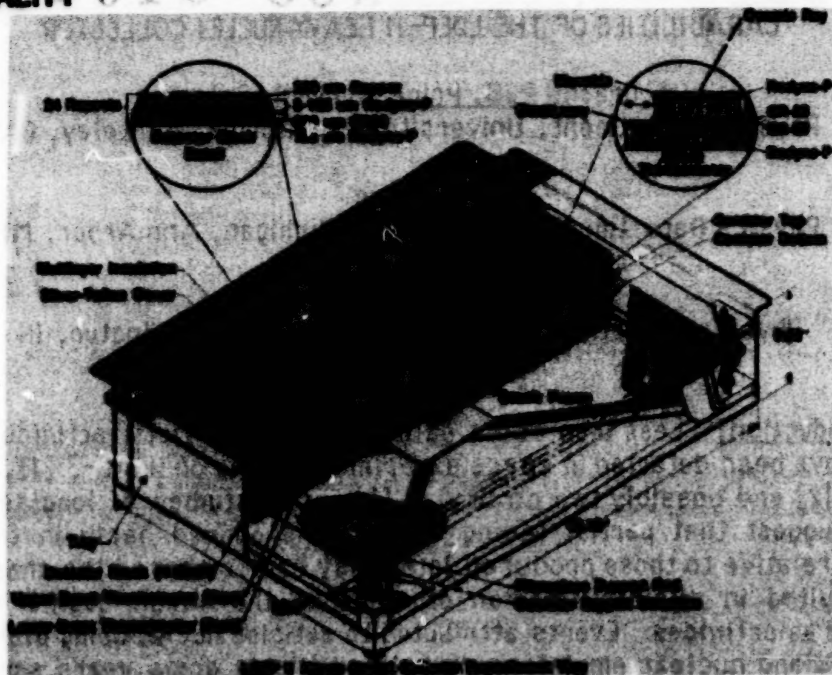
Fig. 1. HNC tray. Composition of stack and design of event thermometer are somewhat different than shown in drawing.

average detector temperature. Thus, each stack is sealed in 0.3 bar of air in a thermally isolated canister shielded from space with multilayer insulation and passive thermal coating, and each stack contains an event thermometer that enables the temperature of the stack at the time of passage of each heavy nucleus to be determined by measuring the displacement of a sliding plastic track-recording sheet with respect to the stack. The sliding sheet is driven by a plunger actuated by a silicone liquid whose volume depends on temperature.

Calibrations at the LBL Bevalac with relativistic beams of U, La, Kr, and Fe ions [5] enabled us to develop improved detectors of two classes: a polycarbonate plastic, Rodyne-P, with outstanding resolution in the region $50 < Z < 120$, and a poly- (allyl diglycol carbonate) plastic, CR-39(DOP), containing 1% dioctyl phthalate and 0.01% of an antioxidant, with outstanding resolution in the region $10 < Z < 70$. (See Fig. 2.) For fully stripped nuclei with $Z < 80$ passing through many sheets, we have verified that the resolution improves as $1/\sqrt{n}$, where n is the number of etchpits measured along the trajectory. For relativistic uranium, an electron is often retained in passage through more than one sheet, with the result that the resolution improves much less rapidly than $1/\sqrt{n}$. We showed that periodic insertion of copper foils in the stack eliminates the correlation in effective charge from sheet to sheet and restores the $1/\sqrt{n}$ dependence [6]. Use of copper, with its high Z, in place of plastic of equivalent mass thickness reduces the fraction of events that fragment within the stack.
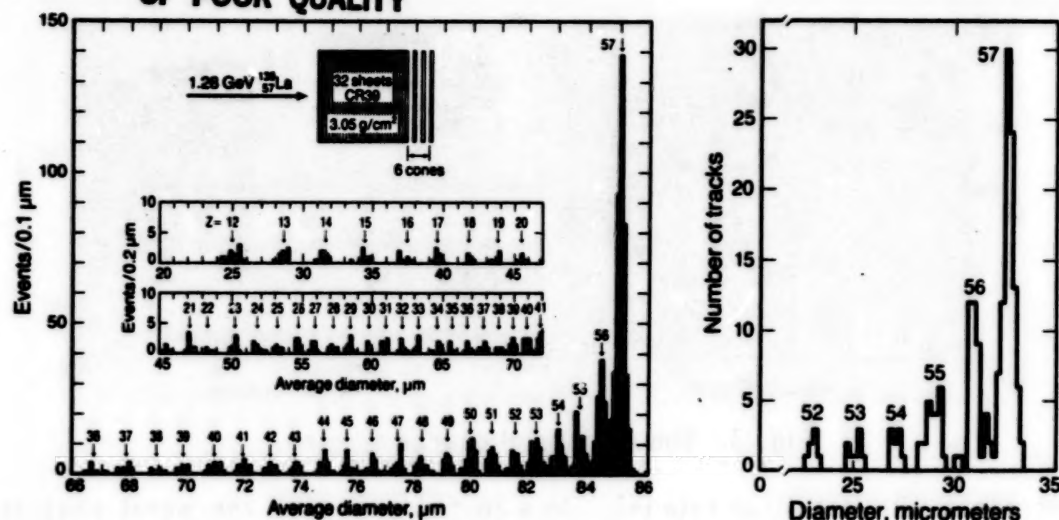
Fig. 2. Bevalac tests showing ability of CR-39 (on left) and Rodyne-P (on right) to resolve individual charges using only a few successive etch pits.

Monte Carlo simulations of detector response enabled us to optimize the sequence of Rodyne-P, CR-39, and copper sheets so as to maximize charge resolution and minimize fragmentation loss within a weight constraint of ~8.7 g/cm^2 per tray. The 41 actinide stacks contain 59 Rodyne-P, 18 CR-39, and 28 copper sheets (not in that order) each 250 microns thick. The four mid-Z stacks contain more CR-39 than Rodyne-P sheets. The weight ratio Cu/plastic = 2.57 corresponds to 0.83 of an interaction length for uranium at normal incidence. For an assumed fractional standard deviation in measured cone length of 1% (2%), the charge resolution at uranium ranges from 0.19e (0.21e) at 1 GeV/amu to 0.21e (0.48e) at 4 GeV/amu. For calibration purposes, two sheets in each stack will be irradiated with a low density of uranium ions over their entire surface before the mission.

Figure 3 shows two Monte Carlo simulations. On the left is the charge spectrum of events with Z ≳ 70 expected if the source of cosmic rays is entirely material with solar system composition. On the right is the charge spectrum expected if the cosmic rays consist of an equal mixture of material with solar system composition and of 10 million year-old r-process material. In a six year mission, as little as 20% admixture of r-process material would lead to a detectable number of plutonium and curium events. Such an admixture cannot be ruled out by HEAO-3 and Ariel-6 data.

4. Data Analysis. In a 28.5 degree orbit the earth's field will eliminate background tracks of slow, highly ionizing galactic iron nuclei and of solar flare particles. Recoil nuclei produced in interactions of trapped protons in the detector will have no significant effect on the insensitive Rodyne-P sheets and will give rise to a background of short etch pits in CR-39 which, on the basis of accelerator simulations, will not seriously degrade detector performance. The dependence of detector response on temperature
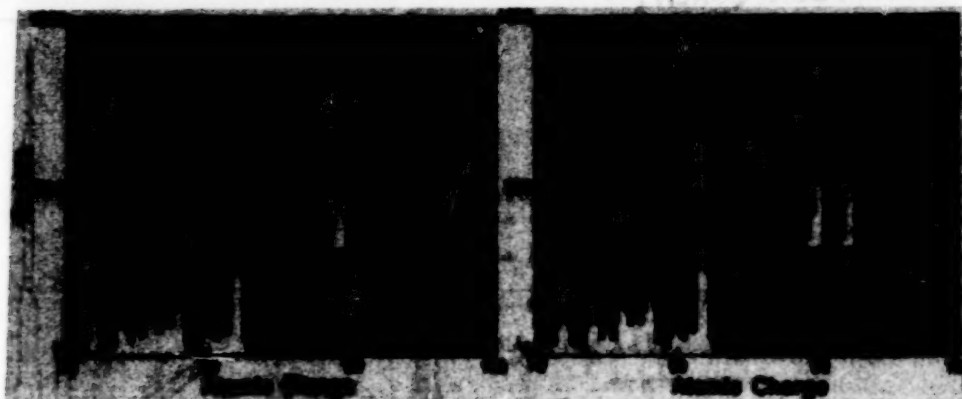
Fig. 3. Simulations of charge spectra.

increases with ionization rate [4]. In a 28.5 degree orbit the worst case is for a ~1 GeV/amu uranium ion, for which the apparent charge shifts by ~0.1e per deg C for Rodyne-P. Passive thermal coatings limit the temperature excursions to ±19 degrees C at the worst locations and ±5 degrees C at the best locations. These temperatures will be measured with adequate sensitivity by the event thermometer. Because all nuclei reaching the detector will be minimum-ionizing, the etching rate for a given plastic type will depend only on Z. For elements up to bismuth, measurements of etch pit elliptical mouths will suffice; for thorium and uranium both the mouth and the entire profile will be measured, using a three-dimensional image-analysis technique [7] illustrated in Fig. 4. We expect roughly 5000 events with Z > 60. About 5×10^5 etch pits will have to be measured. Commercial image processors can be used both to locate events and to perform measurements.
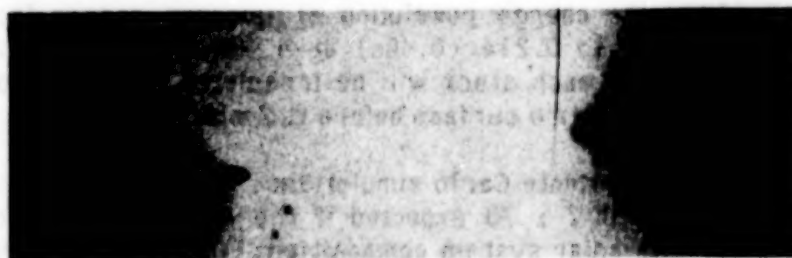
Fig. 4. Digitized, projected image of an inclined etched uranium track.

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ULTRAHEAVY COSMIC RAY TRACKS IN METEORITES:
A REAPPRAISAL, BASED ON CALIBRATIONS WITH RELATIVISTIC IONS

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Experiments have been carried out on tracks of high
energy U ions in olivine, a common meteoritic mineral.
The results offer an explanation for the lack of success
of previous attempts to derive the Ultraheavy Cosmic Ray
composition from the study of tracks in meteorites. They
also suggest how such experiments should be performed.
The methods we are testing are described and
illustrated.

1. Introduction

Prompted by the observation that the Cosmic Ray actinide abundance
is extremely low (1,2), and difficult to measure with a satellite born
experiment, a study of heavy ion tracks in a meteoritic mineral
(olivine), has been started in our laboratory (3), to reevaluate the
feasibility of a measurement of this abundance by means of tracks in
meteorites. To this end, experiments have been carried out, which made
use of high energy U ions, first to try to better understand the
processes involved in very heavy ion track registration and etching in
a mineral, then possibly, to achieve a real calibration of the
meteoritic detectors.

The last results obtained allow us to fully confirm our statement
(3) that the main difficulties of an Ultraheavy Cosmic Ray abundance
measurement by means of tracks in meteorites would lie in the etching
process itself. They demonstrate that, with classical techniques, and
for very heavy ions, one should not expect any relationship between ion
atomic number Z and etched track length. However, techniques can be
devised to restore this relationship. Here we summarize what we have
learnt about heavy ion tracks, without going into technical detail,
before briefly describing the methods we are presently testing and the
first results obtained with them, which make us reasonably optimistic
about the chance of succeeding.

Fig. 1. see caption on last page of paper.
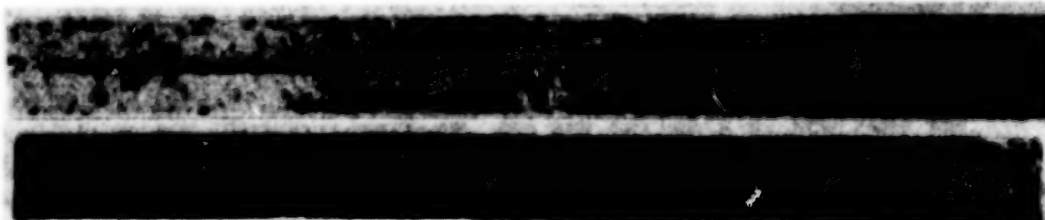
2. Heavy ion tracks: results and implications

Most important is the observation that the track etch rate in olivine (and probably in other mineral track detectors as well) is not only governed by the radiation damage intensity, but also by the etching chemistry (4). The etch rate may be limited, by the etching process, to a much lower value than would be allowed by the radiation damage intensity alone. In addition, the etch rate allowed by the etching process decreases as etching proceeds (i.e. as the etched track length gets longer). For relatively short tracks (i.e. "light" ions) this is generally not of much importance. But for very long tracks, it turns out that after some time, the etch rate becomes so low, that etching finally stops, although the remaining part of the latent track is still potentially etchable (5). Thus, with the usual techniques, in which a track is revealed from one point, generally by means of a crystal fracture - natural or artificial - which intersects it, and through which the etchant can penetrate, the long tracks can only be partially revealed. Since the length of the etched portions are only determined by the etching chemistry, they do not reflect the atomic numbers of the ions which induced the tracks. This may explain the lack of success of previous experiments.

In order to maintain the relationship between track length and Z, one has to reveal the whole etchable track length. For that, a method must be used, which allows the etchant to reach every track at many points along the ion path, so that the revelation of a long track comes to that of many short portions of it.

3. Methods for proper revelation of long tracks

We are presently testing 2 closely related methods allowing the complete revelation of any track. Both make use of medium energy (10-20 MeV/u) heavy ion irradiations, and are variants of the TINT and TINCLE techniques (6). In the first one, olivine crystals are bombarded by a low intensity heavy ion beam (about 10^6 ions per cm^2). Upon etching, the tracks of these ions allow the etchant to penetrate inside the crystals, and reveal the long tracks which they happen to intersect. Each long track intersects many of these "feeding" tracks. In the second one, the crystals are bombarded by a much higher flux ($\sim 10^9$ cm^{-2}), through a mask, sufficiently thick to stop the ions, leaving them pass only through regularly spaced, narrow, parallel slits. Upon etching, the tracks of these ions in turn make sort of parallel grooves in the olivine, through which the long tracks, which cut many of them, can be entirely revealed. These techniques have been applied to the revelation of tracks of 190 MeV/u U ions from the Bevalac, and gave

Fig. 1. cont'd.
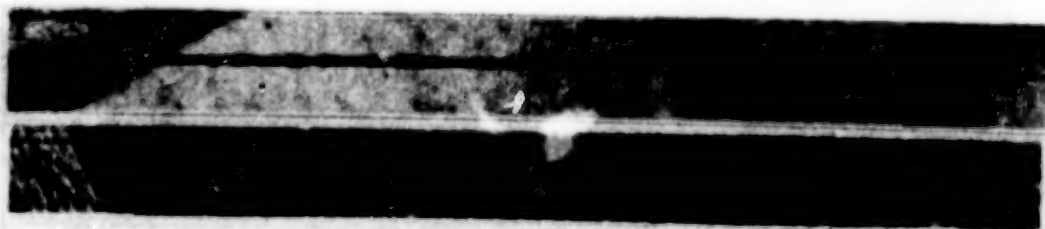
satisfactory results.

As an illustration, a photomicrograph of a U ion track in olivine, revealed by the TINT technique, is shown in Fig.1 (top), which has been cut into 4 parts, one on each page of the paper. The path of the 190 MeV/u U ion is parallel to the plane of the figure. The ion entered the crystal on the right hand side (this page) and came to rest on the left hand side (first page). The crystal has also been irradiated by 14 MeV/u Pb ions from the GSI accelerator (Darmstadt, FRG), perpendicularly to the plane of the figure. The tracks of these ions (seen as black dots on the photo) allowed the revelation of the track of the high energy U ion. It is seen that this track is etchable over the whole ion range ($\sim$2.8 mm) contrary to what we announced earlier (3), misled by an etch induction time effect (4,5). With usual techniques, less than one half of this length can be revealed (5). The high energy part of the track appears discontinuous. This is because the radiation damage intensity, linked to dE/dx, is getting lower in this region, so that in turn the etch rate is very low, and the different portions of the track have not been etched enough to meet.

This part is also the most thermally fragile, and may be responsible for a large broadening of the track length distribution corresponding to a given Z, for Cosmic Ray tracks in meteorites, because of differential annealing in space. The solution to maintain the charge resolution, may be to make length measurements after a stronger annealing in the laboratory (3,7). In Fig.1 (bottom) two 190 MeV/u U ion tracks can be seen (with some difficulty) after partial annealing by heating at 425°C during 5 hours. The length of the tracks have been reduced to 1.1 mm (so that they are seen only on the first 2 parts of the figure). After such a thermal treatment, the tracks of Kr and lighter ions are completely erased, and those of Xe ions reduced to 80 μm. The best conditions for an ion identification experiment in the U region are still to be determined. This will be done by comparing the results obtained for high energy U ion tracks with those for Au ions of a similar energy, which we should get at the Bevalac in the near future.

4. Conclusion

We feel that the results we have obtained, thanks to modern heavy ion accelerators, are extremely encouraging, and suggest that tracks in minerals might serve for ion identification purposes. Of course, tracks are tricky, and success is far from being certain. However, we may soon switch over, with some confidence, to real Cosmic Ray tracks.

The author is much indebted to H.J Crawford and D.E. Greiner

Fig.1. cont'd.

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Fig.1. Top: photomicrograph of the track in olivine of a 190 MeV/u U ion from the Bevalac, revealed by the TINT technique. The photo has been cut into 4 parts. The ion entered the crystal on the right hand side (this page) and came to rest on the left hand side (first page of the paper). The feeding tracks (14 MeV/u Pb ions) perpendicular to the plane of the figure, are seen as black dots. For the discontinuous appearance of the U ion track at the high energy end, see text.
Bottom: same as top, but here, the tracks have been partially annealed (5 h at 425° C). Their etchable length has thus been reduced, and they are seen only on the first two pages of the paper.

100 µm

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EXPERIMENTAL TEST FOR INTERPRETING THE INCREASE IN SENSIBILITY
OF DOPED CR-39.

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1. Introduction.   In recent years the sensibility of CR-39 to nuclear tracks has been increased by doping the corresponding monomer with dioctyl phtalate. At this regard, two theoretical approaches are currently managed to explain this phenomenon: either the doping react with the active radicals in the chain blocking them, stopping crosslinking between chains, or alternatively that the doping gets between them giving wider space between the crosslinked chains.

We delimitate the contribution of each one of these effects in increasing sensibility by applying experimental techniques that will only block the active radicals of the chain.

Since the discovery that dioctyl phtalate (DOP) as a dopant, increases the sensibility of the plastic CR-39 [4], other dopants had been tested. This dopants were generally heavy phtalic esters, as was originally suggested in [4].

We believe that phtalic esters may have twoo possible ways of reacting. Either they can react completely with the active radicals in the monomer bloking and by this stopping crosslinking, or, as they have two reactive sites, they can react with two monomers belonging to two different chains, and by this not to stop crosslinking, but widening the space between crosslinked chains.

Terephtalic esters are suitable dopant openers of crosslinked chains and had also been used showing no great difference in sensibility as compared to the use of phtalic esters.

Here we use benzoic esters, which would be considered as blockers having just   only one reactive site, as dopants, to see if they can increase the sensibility of CR-39.

An increse in sensibility with benzoic esters compared to the phtalic or terephtalic esters, would prove that the sensibility in CR-39 is increased by th dopant to stop crosslinking and not by widening the space between crosslinked chains.

2. Theory. When the monomer- dietilen glycol bis allyl carbonate- is catalyzed by the initiator, the monomer forms what is called free radicals. This free radicals are able to combine themselves within each other to form the polymer chain. However the free radicals of this monomer have two free electrons at both ends of the monomer molecule, which can become two covalent bonds at the ends of the molecule. This makes it possible for different chains which have only use one of the free electrons

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to make the chain and leave the other electron for possible interaction between chains to form a covalent bond between them. This is what is call crosslinking.

If a phtalic ester (heavy) is added when polimerization starts, then the free radicals of monomer induce an inestability between the carboxilic group in the ester and the heavy chain attached to it; causing the ester to break also in free radicals precisely in this bond. The carboxilic group free radical has two oxigens with one free electron each, capable to react and form a covalent bond. So it can react with one monomer in one chain and at the same time, with another monomer in another chain, therefore widening the space between these two crosslinked chains. However, it can happen that only one oxygen has lost his heavy chain and just one electron is now available for reaction. If this happens then the ester will react with only one monomer in one chain, thus blocking that possibility for crosslinking and by this reduce and eventually stop the possibility for crosslinking. On the other side the heavy chain free radical can only interact as blocker.

The purpose of using benzoic esters instead of phtalic or terephtalic esters is that when breaking in free radicals, they can only have one electron for forming a covalent bond. Therefore they will only work stopping the crosslinking between chains. If the sensibility is the same as with the other esters, then phtalic esters work as blockers. If the sensibility decreases, then the phtalic esters work as openers.However if the sensibility increases, then we can not say anything about the work of the phtalic esters but a better dopant has been found.

3.Experimental. Five different preparations were made using the french monomer C.A.D. from the Société Française D'organo-synthèse. Each preparation was polymerized using as initiator 3% by weight of asoisobutironitryl (AIBN) from Dupont (peroxidicarbonates were not available in our country), and four of them were dopped with different esters according to TABLE I. All five polymers were polymerized at the same time, in the same oven with a thirtytwo hour curing cycle [1],[2].

TABLE I.- INITIATOR AND DOPANT USE IN EACH POLYMER.

PREPARATION N°	NAME	INITIATOR	INITIATOR CONC.	DOPANT	DOPANT CONC.
1	CR-39	AIBN	3%	—	—
2	CR-39(DOP)	AIBN	3%	DOP	3%
3	CR-39(MB)	AIBN	3%	MB	3%
4	CR-39(BB)	AIBN	3%	BB	3%
5	CR-39(SB)	AIBN	3%	SB	3%

AIBN= asoisobutironitryl; DOP= dioctyl phtalate; MB= methyl benzoate; BB= benzyl benzoate; SB= sodium benzoate.

After the curing cycle was completed, the plastics thus obtained where soft and flexible. We irradiated them, together with some samples of CR-39 (DOP) from Pershore Mouldings Ltd., with α-particles at different energies. We then etched them in a solution 25% NaOH at 70°C in three steps. A first step of two hours, a second one of two hours nineteen minutes and a third one of three hours .

4. **Preliminary inference.** At the time this confirming abstract was done, analysis of the irradiated plastics was in progress. The analysis will end with calibration curves describing the track velocity of attack as a function of the residual range, which would show the sensibility of each polymer compared to CR-39 (DOP) by Pershore.

Though analysis is not yet complete, some preliminary inferences can be made: From the size of the tracks in our five plastics compared to the size of the tracks in the CR-39 (DOP) from Pershore,we can infer that the sensibility of our plastics should be about the same as the CR-39 (DOP) from Pershore. Though, this should not be conclusive since calibration curves have not been obtained yet.If this inference results in becoming true, we would have proved then, that DOP works as a blocker and not as an opener that widens the space between crosslinked chains.

At the moment being, we have a conclusive result. This is that the tracks in the polymer doped with sodium benzoate are very hard to analyze since the polymer is quite turbid.

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Energy Spectrum and Arrival Direction of Primary Cosmic Rays of
Energy above 10^{18}eV

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Abstract

The observation of ultra high energy cosmic rays with 20km^2 array
has started at Akeno. The preliminary results on energy spectrum and
arrival direction of energies above 10^{18}eV are presented with data
accumulated for four years with the 1km^2 array, for two years with the
4km^2 array and for a half year with the new array. The energy spectrum is
consistent with the previous experiments showing the flattening above
$10^{18.5}$ eV.

1. Introduction

The detailed study on the energy spectrum and the arrival direction
distribution of ultra high energy cosmic rays gives us the information
about their origin, acceleration and propagation. There are still
discrepancies among experimental results reported, especially in arrival
direction distribution at highest energies. In order to clear up these
problems, it is essential to increase the statistics. At Akeno the
operation of the 20km^2 array has started. In this paper, the preliminary
results about energy spectrum and arrival direction of EAS above 10^{18} eV
are reported.

2. Experiment

The experiments have been carried out
with 3 different arrays, 1km^2, 4km^2 and
20km^2. The arrangement of 1km^2 array is
described in Hara et al[1]. For 1km^2 array,
the data of 4 years are accumulated. The
observation with 4km^2 array started at 23rd
Dec. 1982[2] and continued until 26th Dec.
1984. The 20km^2 array has been in partial
operation from 8th Sep. 1984 and full
operation including the 4km^2 array from
27th Dec. 1984. The detector arrangement
of 20km^2 array is described in Teshima et
al[3].

The trigger requirements of 20km^2 array
are 6-fold coincidence of neighbouring
detectors of 23 deployed in about 1 km
separation with each other. The
discrimination level of the signal is 0.5
particle equivalence per detector of 2.25m^2
area.

In this experiment about 250 EAS's of
energy above 10^{18}eV and 5 EAS's of above
10^{19}eV are observed.
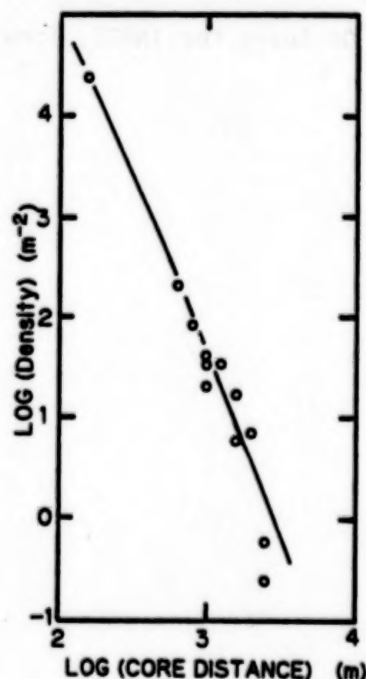
Fig.1(a) The lateral
distribution of
the largest event.
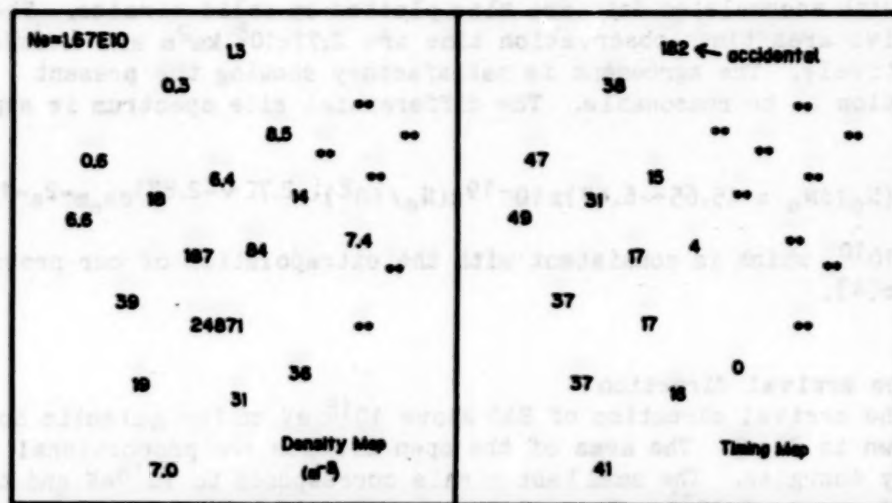
Fig.1(b)   Fig.1(c)

3. The largest event at Akeno

In fig.1 are shown (a) the lateral distribution of electrons, (b) the density map and (c) the arrival time sequence of each detector of the largest event observed so far at Akeno. Numbers of particles per 1 m² are typed on the detector position. In (c) the arrival time differences between each detector and that of the fastest incident particle(indicated by 0) in a unit of 100 ns. This event was recorded in a period under construction of the 20km² array. The size of total electrons is 1.67x10¹⁰ and the zenith angle is 30.3 degree. The core hits inside the array. The estimated primary energy is about 3x10¹⁹eV.

4. The electron size spectrum

The electron size spectrum is derived only from the data of EAS's whose cores hit inside the array, because the error in size determination for those outside the array is so large that the spectrum is possibly deviated as described in Teshima et al[3]. Since the collection efficiency of the new array is not 100% for the showers smaller than 10⁹, the effective area is estimated by analyzing 100,000

Fig.2 The electron size spectrum.

artificial showers simulated by the Monte Carlo method, which distribute uniformly over the wide area following the size spectrum with exponent of -3. The collection factor due to the triggering inefficiency and the error of size determination can be estimated by reconstructing the size spectrum of these artificial showers. The size spectrum thus corrected is shown by open circles in fig.2. The new spectrum obtained by the 1 km²

array with accumulated data are also plotted by solid circles. The effective area times observation time are 2.77×10^8 km^{2}s and 6.08×10^7 km^{2}s, respectively. The agreement is satisfactory showing the present correction to be reasonable. The differential size spectrum is expressed by

$$J(N_e)dN_e = (5.65 \sim 6.47) \times 10^{-19} \times (N_e/10^8)^{(-2.72 \sim -2.87)} dN_e m^{-2} s^{-1} sr^{-1},$$

up to 10^{10}, which is consistent with the extrapolation of our previous results[4].

5. The arrival direction

The arrival direction of EAS above 10^{18} eV on the galactic coordinate is shown in fig.3. The area of the open circles are proportional to the primary energies. The smallest circle corresponds to 10^{18}eV and the largest one to 3×10^{19}. These data are the compilation of 1km^2, 4km^2 and 20km^2 array. The center of the figure is $(l_{II}, b_{II}) = (120, 0)$. The dashed lines indicate the longitude and latitude of equatorial coordinate. The exposure is almost uniform along the longitude lines expressed by the dashed circles, but not along the latitude lines.
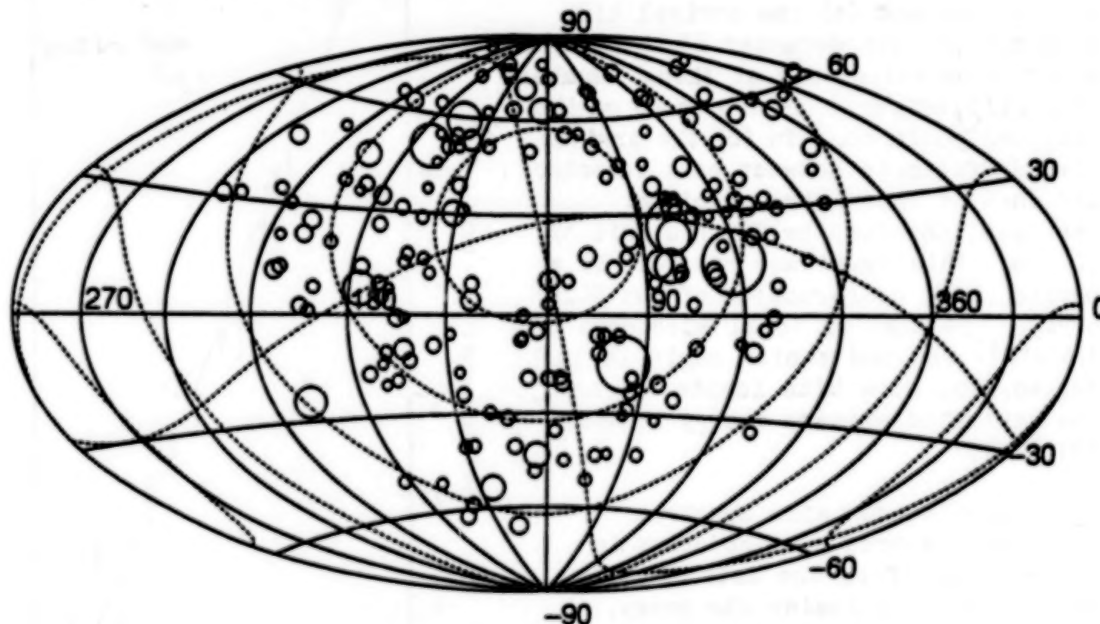
Fig.3 The arrival direction distribution of EAS's above 10^{18}eV on the galactic coordinate.

6. Discussions

The primary energy spectrum is derived from the present size spectrum by multiplying the conversion factor which was derived at smaller size regions as $w \times R = 3.9 \times (N_e/10^6)^{-0.105}$ GeV[4]. Where w is the conversion factor from electron size at the maximum development, 1.4 GeV[5] and R is the ratio of the shower size at maximum to the size at 920gcm^{-2}.

In fig.4 the primary energy spectrum derived from the data of 4km^2 array and 20km^2 is shown by the open circles and compared with the previous experiments. The total exposure is about 10 km^{2}s·year for the

showers of 10^{19} eV. This result shows the good agreement with our
previous result with the Akeno $1km^2$ array[4] at energy region between 10^{17}
eV and 10^{18}eV. Above 10^{18}eV the present spectrum is consistent with the
results of Haverah Park[4], Yakutsk[5] and Sydney[6] showing the
flattening. Here the Sydney results are plotted by applying the conversion
factor used in ref[4].

Though the statistics is not enough, some interesting features can be
seen around 10^{18}-10^{19}eV. That is, the largest showers are clustered
around the Cygnus direction and the spectrum shape does not follow the
simple power law.
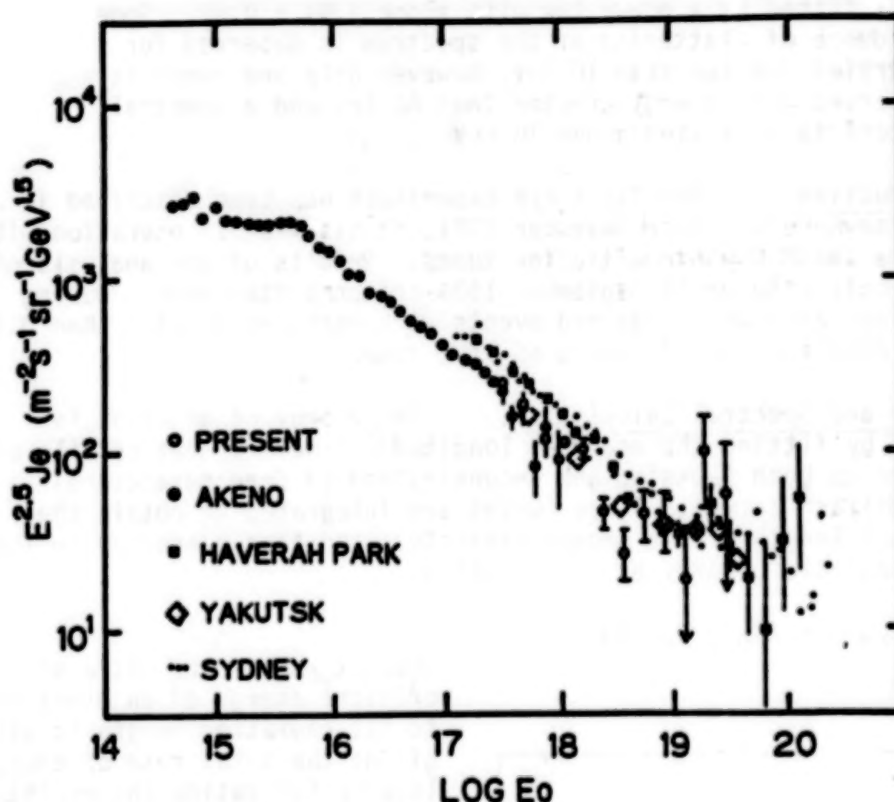
Fig.4 The primary energy spectrum.

Acknowledgements

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ULTRA HIGH ENERGY COSMIC RAY SPECTRUM

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ABSTRACT

Ultra-high energy cosmic rays have been observed by means
of atmospheric fluorescence with the Fly's Eye since
1981. The differential energy spectrum above 0.1 EeV is
well fitted by a power law with slope 2.94 ± 0.02. Some
evidence of flattening of the spectrum is observed for
energies greater than 10 EeV, however only one event is
observed with energy greater than 50 EeV and a spectral
cutoff is indicated above 70 EeV.

1. Introduction.

The Fly's Eye experiment has been described in detail elsewhere[1]. Since November 1981, it has been in operation with 67 mirrors and 880 photomultiplier tubes. Results of the analysis of the data collected up to September 1984 are presented here. During this period, 2408 well measured events with energies greater than 0.1 EeV were detected in 1278 hours of live time.

2. Energy and Spectral Calculation.

The energy of an event is estimated by fitting the measured longitudinal development profile of the shower to both Gaussian and unconstrained (3 free parameters) Gaisser-Hillas[2] curves. These curves are integrated to obtain the total track length of the shower particles, and then converted to total 'electromagnetic' energy by the relation

$$E_{em} = \epsilon_0/X_0 \int N_e(x)dx$$

where ϵ_0/X_0 is the ratio of critical energy of an electron to its radiation length in air, giving the total rate of energy loss by ionization and excitation. The loss rate used here is 2.18 MeV g cm^{-2}. Total energy of the primary particle is then calculated by correcting the 'electromagnetic' energy for undetected energy using estimates of this lost energy derived by Linsley[3]. These range from 13% at 0.1 EeV to 5% at 100 EeV. This method of energy estimation relies only on low energy interactions and is essentially model independent. Shown in Fig. 1 is the raw energy distribution of observed events.

Figure 1. Raw Energy Distribution of Fly's Eye Data.

To obtain the energy spectrum from these data, the energy dependent Fly's Eye aperture must be calculated. This has been done using a Monte Carlo simulation of the system. In this simulation quasi-random trajectories and first interaction depths for the events are chosen from an isotropic distribution, and the showers are developed using the constrained Gaisser-Hillas[2] parameterization and shapes obtained from the real data sample, thereby ensuring consistency between the simulation and the data base. Triggering Monte Carlo events are stored and analyzed using the analysis programs which are used on the real data. The sensitive aperture of the Fly's Eye is then calculated from the ratio of accepted to tried Monte Carlo events. Scatterplots of the distribution of events in impact parameter and energy for both (a) Monte Carlo and (b) real events are shown in Fig. 2. There is excellent agreement between these distributions, indicating that the simulation is a good representation of the Fly's Eye. Figure 3 shows the effective Fly's Eye aperture calculated from the simulation.

(a)   (b)
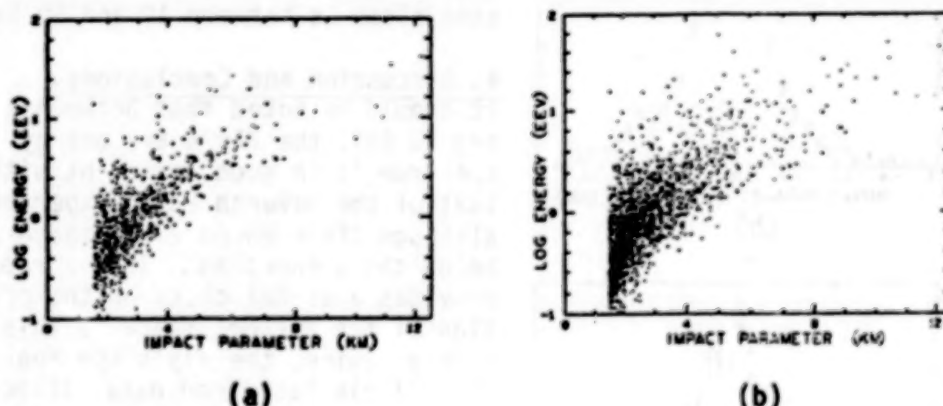
Figure 2. Energy vs Impact Parameter Scatterplots for (a) Monte Carlo and (b) Fly's Eye Data.

The self-consistency of the analysis programs is also checked by the processing of the Monte Carlo events with the analysis routines and comparing the results with the original Monte Carlo event parameters. Response functions for (a) zenith angle, (b) impact parameter and (c) energy are shown in Figure 4.
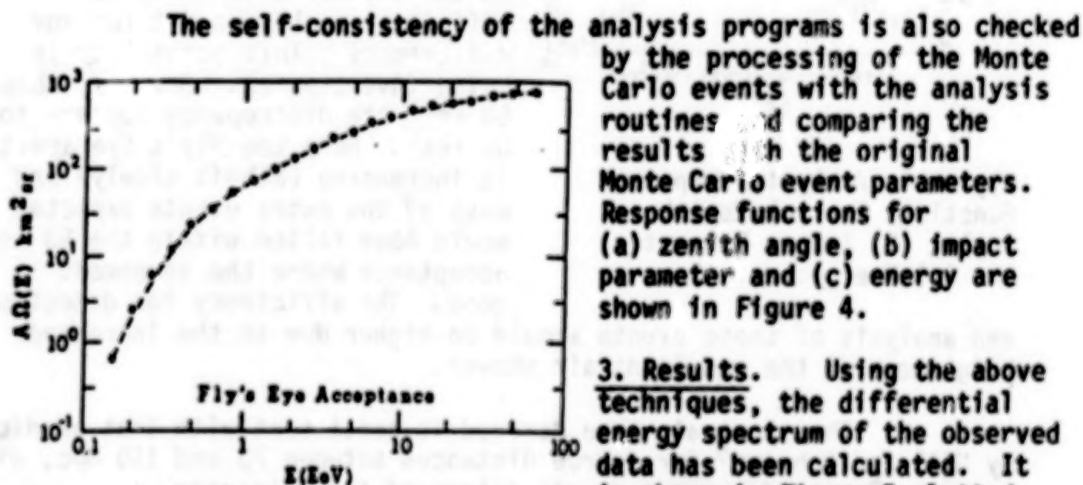
Figure 3. Fly's Eye Sensitive Aperture.

3. Results. Using the above techniques, the differential energy spectrum of the observed data has been calculated. It is shown in Figure 5 plotted as $E^3 j(E)$. The spectrum is essentially flat between 0.1 and 10 EeV with a slope of 2.94 ± 0.02. Between 10 and 50 EeV, there is the appearance of a bump,

(a)

(b)

(c)
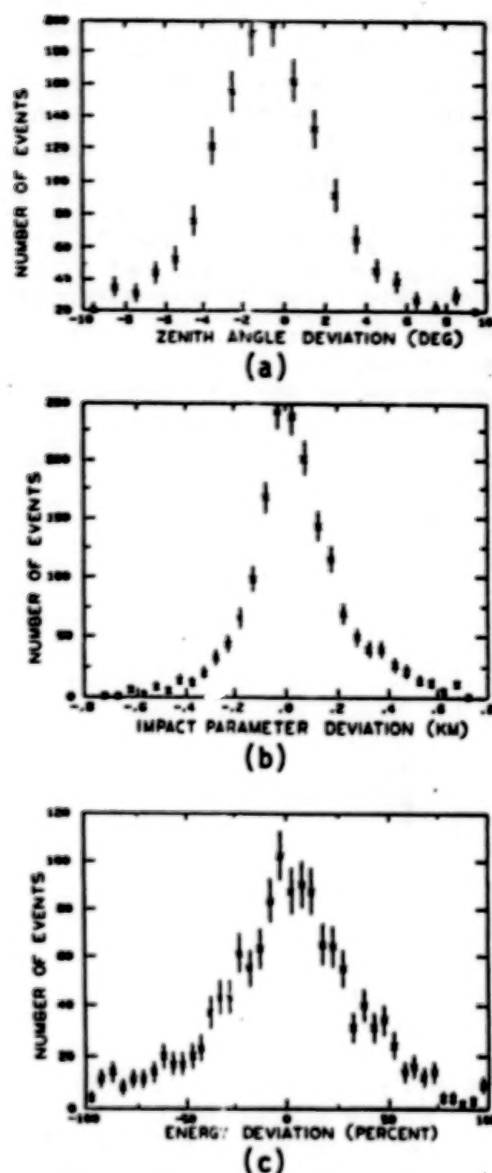
Figure 4. Analysis Response
Functions for (a) Zenith
Angle, (b) Impact Parameter,
and (c) Energy.

with 62 events in this interval
compared with 46 that would be expec-
ted if the spectrum continued with
the same slope as at lower energies.
Since the uncertainty in this pre-
dicted value is small, the signifi-
cance of the bump is roughly
$16/\sqrt{46} = 2.4\sigma$. If the spectrum
between 10 and 50 EeV is fitted by a
power law, the slope is found to be
2.42 ± 0.27, about 2σ flatter than
the value at the lower energies.
Only one event is observed with
energy greater than 50 EeV. This
should be compared with 11 ± 5 events
which would be observed if the spec-
trum continued above 50 EeV with the
same slope as between 10 and 50 EeV.

4. Discussion and Conclusions.
It should be noted that between 1
and 50 EeV, the Fly's Eye energy
spectrum is in good agreement with
that of the Haverah Park[4] experiment,
although differences exist above and
below these energies. This agreement
provides a useful check on the opera-
tion of the system, since in this
energy regime, the Fly's Eye aperture
is well simulated and data collection
statistics are good. Below 1 EeV,
the acceptance is rapidly changing
and threshold simulations and errors
in the estimates of analysis
efficiency could acocunt for any
differences. This possiblity is
being investigated. However, above
50 EeV, the discrepancy appears to
be real. Here the Fly's Eye aperture
is increasing (albeit slowly) and
most of the extra events expected
would have fallen within the 50 EeV
acceptance where the agreement is
good. The efficiency for detection
and analysis of these events should be higher due to the increased
brightness of the resultant air shower.

The spectral shape derived is consistent with that predicted
by Hill and Schramm[5] for source distances between 70 and 150 Mpc, with
a Greisen[6] cutoff above a recoil pileup of the primaries.

149
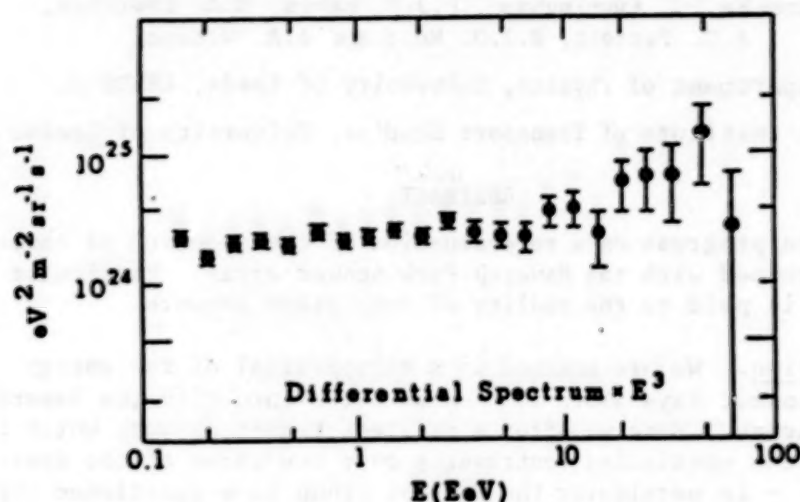
Figure 5. Fly's Eye Differential Energy Spectrum.

5. Acknowledgements.   The support of the United States National
Science Foundation is gratefully acknowledged.

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THE PRIMARY COSMIC RAY SPECTRUM ABOVE 10^{19} eV

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ABSTRACT

We describe progress on a re-evaluation of the spectrum of cosmic
rays determined with the Haverah Park shower array. Particular
attention is paid to the reality of some giant showers.

1. **Introduction.** We are engaged in a re-appraisal of the energy
spectrum of cosmic rays above 10^{18} eV as determined with the Haverah
Park shower array. Here we offer a progress report on work which is
motivated by the continuing controversy over the shape of the spectrum
above 10^{19} eV - in particular the Yakutsk group have questioned the
reality of events of 10^{20} eV - and by the recent re-investigation of the
predicted shape of the spectrum above 10^{19} eV if the sources of these
particles are at cosmological distances (Hill and Schramm 1985).

2. **Cosmic Ray Energy Spectrum.** The differential energy spectrum
derived from our work above 10^{18} eV is shown in Figure 1. Above
3.5×10^{18} eV the spectrum has been updated by the addition of events
recorded to December 1983. A detailed analysis of possible sources of
systematic error has been made taking into account the effects of un-
certainties in zenith angle, lateral distribution fluctuations, core
location and attenuation length, (Cunningham 1982). For energies
between 8×10^{17} and 3.5×10^{18} eV systematic selection effects and
analysis errors dominate over statistical uncertainties and detailed
simulations have allowed a deconvoluted spectrum to be derived. Above
3.5×10^{18} eV the error analysis has been conducted on a shower-by-shower
basis and the statistical errors have been shown to be at least twice as
great as the instrumental errors. We do not yet regard the spectrum of
Figure 1 as our 'final' spectrum as further refinements will be possible
as our detailed knowledge of showers increases but we wish to emphasise
that we have considerable confidence in the durability of the intensities
and energies assigned above 10^{19} eV. The major differences between this
spectrum and those published at Kyoto are (a) the exclusion of events
with $\theta > 45°$ (as we now regard our knowledge of the structure function to
be incomplete above this angle) and (b) use of an energy dependent
structure function measured in showers of $10^{17} - 5 \times 10^{18}$ eV (Coy et al
1981) and in a small number of large showers which fell during the period
of that experiment. The main features of the spectrum are the flattening
above 10^{19} eV and its continuity to just beyond 10^{20} eV. At the Paris
conference we pointed out that the flattening may also be interpreted as
a dip in the spectrum (Bower et al 1981) and suggested that if particles
above a few times 10^{18} eV were of extragalactic origin then the dip might
well be due to electron-pair production. This interpretation has been
confirmed by the detailed analysis of Hill and Schramm (1985).

The Haverah Park and Yakutsk spectra (Vaselev et al 1983) are compared

in the lower part of Figure 1. The spectra are found to agree reasonably well until about 3×10^{19} eV when the absence of large showers in the Yakutsk spectrum becomes apparent.

In recent years a number of $1 \, m^2$ blocks of scintillator have been incorporated in the Haverah Park array making possible a comparison between the model calculation conversion used by the Haverah Park group and the calorimetric approach of the Yakutsk group. We have shown elsewhere that the calibration is good (to within better than 20%) up to at least 5×10^{19} eV and similarly that the Volcano Ranch energy estimates are in accord (Bower et al 1983a, b). Also the Sydney experiment offers evidence of a flattened spectrum above $\sim 4 \times 10^{19}$ eV (Horton et al 1983); that spectrum may extend to 4×10^{20} eV (Linsley 1983). We do not plot the Sydney spectrum here because of uncertainties about the energy calibration.[†]

Figure 1

Haverah Park Spectrum ($\theta < 45°$)
June 1968 – Dec. 1983

× Yakutsk (Vaselev et al 1983)
○ Haverah Park

$\log JE^3 \, (m^{-2} s^{-1} sr^{-1} eV^2)$

$\log E (eV)$
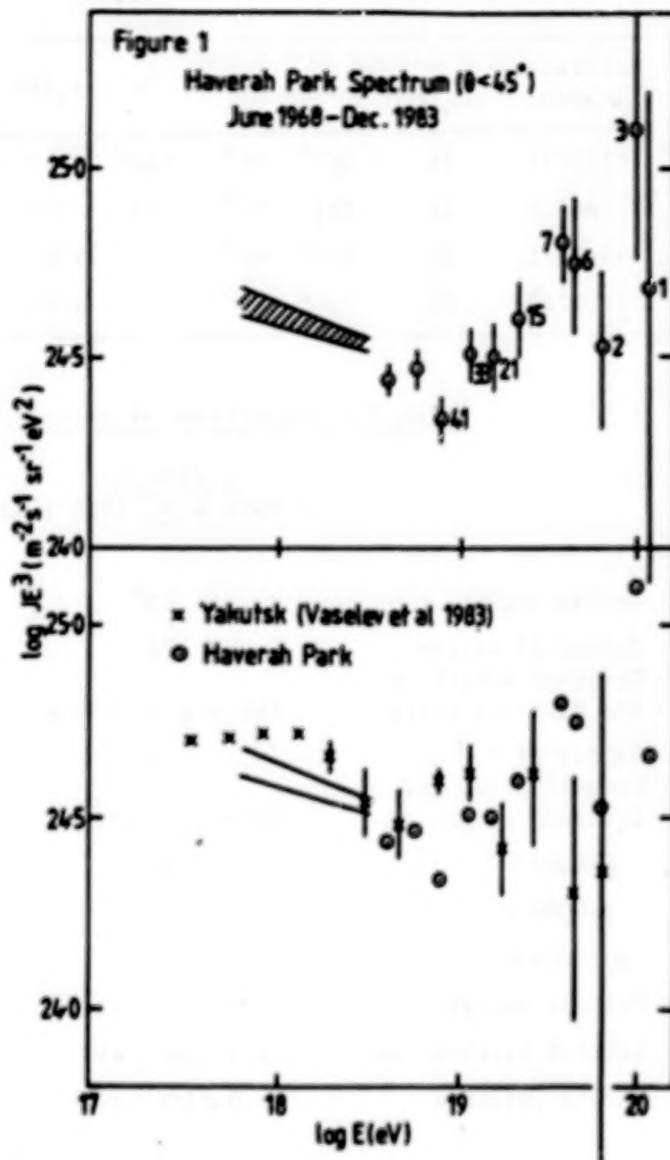
3. **Events of 10^{20} eV.** The 4 most energetic events included in the spectrum have been assigned energies $> 10^{20}$ eV. Brief details of these are given in Table 1; maps of the density pattern observed in each event were published in the World Data Catalogue although the sizes have been slightly altered as a result of the revised lateral distribution function now adopted. Three of the events have risetime information available at one or more of the $34 \, m^2$ detectors and are discussed in that context in HE 4.7-6 (Lawrence et al).

Of the events in Table 1 by far the most outstanding in terms of number of densities and precision of core position is 17684312. Unfortunately this event was recorded in the epoch before scintillator densities were

being recorded. One of the most energetic events with scintillator density information is 21220296, a map for which has been published elsewhere (Bower et al 1983c) and these two events are contrasted in Table 2.

Table 1

Reference number	angle θ	α	δ	b	r_1(m)	Energy (eV)	World Data Catalogue	Rise-times
8185175	35	353°	19°	-40°	443	1.02×10^{20}	p78	None
17684312	35	201°	71°	46°	376	1.05×10^{20}	p86,87	1
9160073	30	199°	44°	73°	1384	1.05×10^{20}	p79	2
12701723	29	179°	27°	78°	1093	1.21×10^{20}	p83	4

Table 2 : Comparison of two giant air showers

	21220296 (J Phys G 9, 1569 1983)	17683412 (World Data Catalogue pp86-7)
Zenith angle	13°	35°
Number of water-Cerenkov detectors and distance range	24 150 < r < 2170 m	50 90 < r < 2500 m
Number of 1 m^2 scintillators and distance range	8 420 < r < 680 m	-
$S(600)$ m^{-2}	157	
$\rho(600)$ m^{-2}	64	105
$\rho_v(600)$ m^{-2}	66	136
Primary energy:		
Yakutsk calibration	5.3×10^{19} eV	-
Hillas relation	5.0×10^{19} eV	1.1×10^{20} eV

The estimated error in the assigned size ($\rho(600)$) for each of these events is $\sim 10\%$; this error includes core location uncertainty, stationary error and allowance for lateral distribution uncertainty and is so small because of the exceptional symmetry in the detector density patterns. The risetime measurements in each event are also in agreement with these analyses. Event 17683412 is unquestionably twice as large as 21220296 which in turn, through the scintillator and water-Cerenkov densities, has two independent energy estimates of $\sim 5 \times 10^{19}$ eV.

In addition to the 4 events discussed above we have recorded a further 4 events which we believe are $\gtrsim 10^{20}$ eV. These are not included in our energy spectrum because they arrived from zenith angles > 45° and/or the

cores fell outside of the array boundary. The flux derived from all 8 events in this total exposure of $657 \, km^2 \, sr \, y$ is $\left(4 \; {}^{+2}_{-1}\right) \times 10^{-16} \, m^{-2} \, s^{-1} \, sr^{-1}$ and is consistent with that deduced for the 4 events of Table 1, namely
$$I(> 10^{20} \, eV) = \left(3 \; {}^{+2}_{-1}\right) \times 10^{-16} \, m^{-2} \, s^{-1} \, sr^{-1}.$$

4. Discussion and Conclusions. The proven existence of cosmic ray events with $E > 10^{20}$ eV demands explanation. Presumably the source of these events must be relatively close to the earth but it can hardly be galactic as $|b| > 40^\circ$ for all 4 events of Table 1. The inferences drawn about the ability of the Cygnus X-3 system to accelerate large fluxes of cosmic ray nuclei to 10^{17} eV/nucleon (Hillas 1984) leads naturally to speculation that a suitably scaled up system, perhaps in the nucleus of an active galaxy, can accelerate particles to 10^{20} eV and beyond.

Our current best estimates of the integral intensities above 10^{18}, 10^{19} and 10^{20} eV are

$$I(> 10^{18} \, eV) = (1.9 \pm 0.2) \times 10^{-12} \, m^{-2} \, s^{-1} \, sr^{-1}$$
$$I(> 10^{19} \, eV) = (2.1 \pm 0.2) \times 10^{-14} \, m^{-2} \, s^{-1} \, sr^{-1}$$
$$I(> 10^{20} \, eV) = (3 \pm 2) \times 10^{-16} \, m^{-2} \, s^{-1} \, sr^{-1}$$

Further details of our analysis will be published elsewhere.

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† After preparation of this paper was completed (22 May 1985) the issue of Physical Review Letters (22 April 1985), which contains the new spectrum deduced from Fly's Eye, reached us. We do not agree with the Fly's Eye group's conclusion that an end to the cosmic ray spectrum has been observed. A comment on their letter is being prepared for submission to Physical Review Letters.

NEW CALORIMETRIC ALL-PARTICLE ENERGY SPECTRUM

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ABSTRACT

Both the maximum size N_m and the sea level muon size N_μ have been used separately to find the all-particle energy spectrum in the air shower domain. However the conversion required, whether from N_m to E or from N_μ to E, has customarily been carried out by means of calculations based on an assumed cascade model. It is shown here that by combining present data on N_m and N_μ spectra with data on 1) the energy spectrum of air shower muons and 2) the average width of the electron profile, one can obtain empirical values of the N_m to E and N_μ to E conversion factors, and an empirical calorimetric all-particle spectrum, in the energy range $2 \cdot 10^6 < E < 2 \cdot 10^9$ GeV.

1. Introduction. The great majority of shower particles are electrons, so it is natural that in the earliest air shower experiments the energy estimates were based on the number of electrons at the observation level. The first estimates (Auger 1939) were too low by about a factor of 4, because 1) the correction for longitudinal development was too conservative, and 2) the energy given to muons, neutrinos and low energy hadrons ($E_{\mu\nu h}$) was ignored. (At the energies in question $E_{\mu\nu h}$ amounts to some 35% of the whole.) The first difficulty stems from the average electron energy being comparatively low ($\sim E_c$, so that electrons are continually absorbed and regenerated. In order to estimate the energy deposited in the atmosphere one must use an integral signal such as the yield of atmospheric Cerenkov or fluorescent light, or else face the problem of accurately evaluating a correction factor that may be as large as a factor 20. By observing showers near maximum development (which generally means at a very high altitude) one can reduce the uncertainty in E_{EM} by minimizing the correction factor. Following this approach, one finds the all-particle energy spectrum by combining measurements of the N_m spectrum with estimates of the conversion factor E/N_m.

The alternative is to use shielded counters, which respond only to muons, and measure the N_μ spectrum, where $N_\mu(>E_\mu)$ is the 'muon size', the number of muons with enough energy to penetrate the shielding. This was done on a very large scale in the SUGAR experiment (Horton et al. 1983) and more recently in experiments at Chacaltaya, Tien Shan and Akeno (Kakimoto et al. 1981, Kirov et al. 1981, Hara et al. 1983). The difficulty with this method is that calculations relating N_μ to primary energy are relatively complex and model-dependent (see for example McComb et al. 1977 and Hillas 1981). Calculations of E/N_m are less affected by these difficulties, but they also require estimating the energy given to muons.

My purpose here is to show that by treating the experimental N_m and N_μ spectra simultaneously, using also experimental data on 1) the energy spectrum of air shower muons and 2) the width of the electron profile, one can obtain conversion factors which are almost entirely empirically

based, and a new result on the all-particle energy spectrum which is al-
most entirely model independent.

2. Relation between maximum size and electronic energy.
The energy dis-
sipated by electrons is given by the track length integral

$$E_{EM} = (E_C/x_0) \int N(x) dx , \tag{1}$$

where $N(x)$ is the number of electrons at depth x g/cm^2, E_C is the criti-
cal energy (=81 MeV in air according to Dovzhenko and Pomanskii 1964),
and x_0 is the radiation length (= 37.1 g/cm^2 in air according to confer-
ence paper HE4.4-4). Writing $E_{EM} = K(E_C/x_0)\sigma N_m$, where N_m is the height
and σ is the width (standard deviation) of the average shower profile,
what can be said about the value of K? Using a Gaussian distribution for
N (surely quite a crude approximation), $K = \sqrt{2\pi} = 2.51$. Using a gamma
distribution, $N = N_0 \xi^q \exp(-q\xi)$ where $\xi = x/x_m$, which can be adjusted to fit
very well (see conference paper HE4.4-5), the value of K ranges from 2.35
for q=6 (small showers) to 2.42 for q=12 (large showers). Thus it hardly
varies at all, so adopting an average value for K, and substituting for
(E_C/x_0), I obtain

$$E_{EM} = (\sigma/192) N_m , \tag{2}$$

where σ is in g/cm^2 and E_{EM} is in GeV, accurate to 1-2%.[*] The profile
width has been measured in the Yakutsk and Utah experiments (Grigoriev et
al. 1983, Baltrusaitis et al. 1985), but only for E $\sim 10^9$ GeV. The ener-
gy dependence is expected on theoretical grounds to take the form $\sigma^2 =
A + BD_{10}\log E$, where D_{10} is the elongation rate per decade, $\approx$ 65 g/cm^2
(Linsley and Watson 1981) and B is a characteristic length of order 60-70
g/cm^2 (conference paper HE4.4-5). Using the Yakutsk-Utah data to fix the
value of A, one obtains $\sigma^2 = 1.1 \cdot 10^4 + 4.2 \cdot 10^3 \log E$ (Linsley 1983),[†] and
finally, by substitution in (2),

$$E_{EM} \approx 0.71 N_m^{1.025} . \tag{3}$$

3. Relation between muon size and $E_{\mu\nu h}$.
There is good agreement among
independent measurements of the energy spectrum of air shower muons
(Atrashkevich et al. 1983 and references therein). This spectrum is
quite hard; almost half of the observed energy is given to particles with
individual energies above 30 GeV. Over the range of shower energies
where it has been studied ($3 \cdot 10^5 - 10^8$ GeV), the shape of this spectrum is
invariant; hence the total energy of the observed muons is proportional
to $N_\mu(>1GeV)$, the number of muons (at sea level) with energy > 1 GeV,
where the proportionality constant equals 10.0±.5 GeV. To obtain the
energy given to neutrinos the observed muons are propagated backward to a
production spectrum. In the air shower region it is found that $E_\nu \sim
0.4 E_{\mu,obs}$, where E_ν includes both ν_μ and ν_e. This result checks with a
forward propagation calculation by Hillas (1981). Experiment based esti-
mates of E_h, the energy deposited by low energy hadrons, range from
0.8 $E_{\mu,obs}$ (Greisen 1956) to 0.3 $E_{\mu,obs}$. Adopting $E_h \sim 0.4 E_{\mu,obs}$ as a
conservative estimate, the total non-electronic contribution is obtained:

$$E_{\mu\nu h} = (18^{+3.5}_{-1.5} \text{ GeV}) \cdot N_\mu(>1GeV)_{sea level} . \tag{4}$$

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[*] An alternative form which may sometimes be more convenient is $E_{EM} =
(x_{hm}/428) N_m$, where x_{hm} is the full width at half maximum (Linsley 1981).
[†] In the energy range of interest here, the simpler formula $\sigma = 130 +
10.2\log E$ is equivalent.

Table 1. *Muon size for a given intensity from various experiments.*

integral intensity $(m^2 sr\ s)^{-1}$	N_μ (>1GeV)		muon threshold (GeV)	Ref.
10^{-6}	2.3×10^4		10.0	VK*
10^{-7}	6.5	"	"	"
10^{-8}	1.6×10^5	"	"	"
"	1.6	"	1.0	Ha@
10^{-9}	3.8	"	10.0	VK*
"	4.0	"	1.0	Ha@
10^{-10}	1.0×10^6		"	"
10^{-11}	2.5	"	0.22	L*@
"	2.0	"	0.70	Dm*
"	3.5	"	0.75	Ho*
"	2.4	"	1.0	Dx
"	2.6	"	"	Ha@
10^{-12}	5.7	"	0.70	Dm*
"	9.1	"	0.75	Ho*
10^{-13}	1.6×10^7		0.70	Dm*
"	2.4	"	0.75	Ho*
10^{-14}	6.4	"	"	"
10^{-15}	1.7×10^8		"	"
10^{-16}	4.5	"	"	"
10^{-17}	1.2×10^9		"	"

* adjusted to 1 GeV threshold
@ adjusted to sea level

Neither this result nor the one expressed by (3) depends on any assumption about the primary composition; they are properties of cosmic rays *as they occur*, in this energy range, at the solar system. As an experimental result, (4) applies to the energy range given above, $3 \cdot 10^5 - 10^8$ GeV. Extrapolation up to 10^{11} GeV is justified unless there occurs some radical change affecting the production of *very high energy* muons and neutrinos.

4. Calorimetric all-particle energy spectrum. Data on the N_μ and N_m spectra are summarized in Tables 1 and 2, in inverse form (N_μ and N_m as functions of integral intensity). The (inverse) all-particle energy spectrum is obtained by adding together E_{EM} from (3) and $E_{\mu\nu h}$ from (4), using tabulated values of N_μ and N_m for the same intensity, in the range $10^{-6}-10^{-12}/m^2 sr\ s$ where there are reliable data for both N_μ and N_m. The result, changed to differential form, is shown in Fig. 1. In case of Table 1 the various N_μ values for a given intensity were averaged; in case of Table 2, the later results at Chacaltaya were used. There is good agreement with the Yakutsk energy spectrum in this range (Efimov and Sokurov 1983), and with Haverah Park results (Cunningham et al. 1980). The present result supports a rather high location, nearly 10^7 GeV, for the transition region where the change of slope (knee) occurs.

5. Other results: conversion factors. As I showed previously, this derivation of the energy spectrum yields as by-products factors for converting N_m and N_μ separately to primary energy, and also yields the fraction of primary energy given to electrons, vs energy (Linsley 1983). These results are shown in Fig. 2. The low value found for E/N_m, $1.3\pm.2$, confirms an important prediction by Hillas (1983). An apparent conflict between results from Chacaltaya and from lower elevations is resolved. The earlier values of N_m (La Pointe et al. 1968) were somewhat too low, but energies were about correct because the conversion factor was somewhat too high. The later values of N_m are more nearly correct, but the energies were too high because the conversion factor was much too high. Although here the conversions, N_m to E and N_μ to E, have been treated symmetrically, the energy dependence of the N_μ-E 'conversion factor' makes this inconvenient in practice. Convenient formulae for representing the

N_μ data in Fig. 2 and Table 1 are:

$$N_\mu(>1GeV)_{s.1.} = E(GeV)^{0.835}/6.8, \quad (5)$$

$$J[>N_\mu(>1GeV)]_{s.1.} = 3 \cdot 10^4 N_\mu^{-2.4}, \quad (6)$$

where J is in $m^{-2}sr^{-1}s^{-1}$.
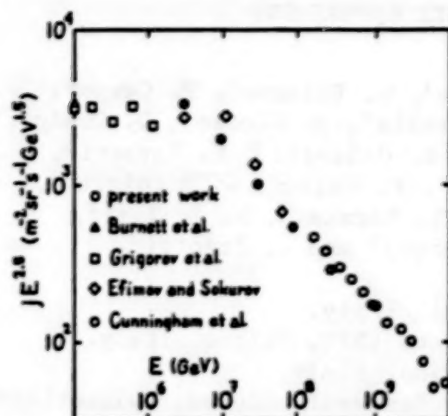
Fig. 1. All-particle Energy Spectrum.
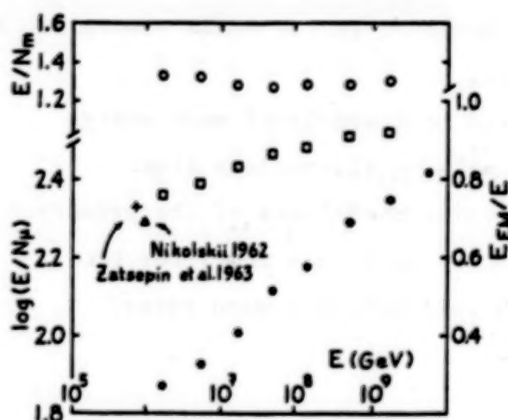
Fig. 2. Other Results. Open circles E/N_m, squares E_{EM}/E (r. h. scale), filled circles $\log(E/N_\mu)$.

Table 2. Maximum size for a given intensity from various experiments

integral intensity $(m^2 sr \ s)^{-1}$	N_m		obs. depth g/cm^2	Ref.
10^{-5}	3.5	x 10^5	210	AI
10^{-6}	1.3	x 10^6	"	A
"	1.3	"	540	LP
10^{-7}	4.2	"	"	"
10^{-8}	1.15	x 10^7	"	"
"	1.30	"	"	K
10^{-9}	3.6	"	"	LP
"	4.0	"	"	K
10^{-10}	1.05	x 10^8	"	LP
"	1.20	"	"	K
10^{-11}	3.2	"	"	LP
	4.0	"	"	K
10^{-12}	1.26	x 10^9	"	"
"	5.	x 10^8	835	L
10^{-13}	1.6	x 10^9	"	"
10^{-14}	1.	x 10^{10}	"	"

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PRIMARY COSMIC RAY SPECTRUM IN THE $10^{13}-10^{16}$ eV
ENERGY RANGE FROM THE NUSEX EXPERIMENT

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INTRODUCTION

The single muon intensity has been measured in the NUSEX experiment at
various depth up to 10,000 hg/cm² s.r..

These intensities have been converted to a sea-level muon energy
spectrum which is used to derive the primary all-nucleon flux.

From these data we are able to determine the slopes of the primary
proton and helium spectra, which are thus used in a model for the
primary composition producing the observed multiple muon rates.

DATA REDUCTION AND PRIMARY SPECTRUM

The NUSEX detector is located in the Mt. Blanc tunnel at a vertical
depth of about 5000 hg cm⁻² s.r. It consists of a cube of 150 t mass
and 3.5 side, made of 136 horizontal planes 1 cm thick, interleaved with
planes of tubes of 1 cm x 1 cm cross section, operating in the limited
streamer mode. More details are reported elsewhere [1].

20429 muon events crossing at least 10 layers were recorded in a zenith
angle range 0° - 75° during an effective working time of 18,946 hours
from June 1982 to December 1984. The number of events for different
multiplicities are reported in table 1.

The single muon intensity at different depths has been found using the
procedure of Ref. 2. The general relation

$$I(h,\theta) = I_\mu^{\pi,K}(h) \cdot G^{\pi,K}(h,\theta) + I_\mu^P(h) \cdot G^P(h,\theta) \tag{1}$$

has been fitted to the data. Here the π and K superscripts refer to
conventional muons from π and K decay, the p superscript to prompt muons
from charmed particle decays.

The angular enhancement functions have been calculated in Ref. 3 . The
intensity of prompt muons is found < 4% on the considered range of
depths, so that the second term in (1) has been neglected. The muon
intensity is reported in Fig. 1. together with the intensity points
measured with the spark chamber apparatus located in the Mt. Blanc tunnel,
garage 27. The agreement is excellent, so giving a unique intensity-depth
set of measurements from 3900 to 10000 hg/cm² s.r. very well represented
by the relation

$$I_\mu^{\pi,K}(h) = (7.63\pm.48)\cdot 10^{-7}\exp[-h/(810.44\pm.84)]\,cm^{-2}s^{-1}sr^{-1}$$

Following the procedure of Ref. 2 we derive the primary all-nucleon
spectrum in the relevant energy range $10^{13} \div 2\cdot 10^{14}$ eV :

$$\frac{dN}{dE_o} = (4.8\pm.2)E_o^{-2.79\pm.03}\; cm^{-2}s^{-1}sr^{-1}GeV^{-1}$$

The rates of events with exacty n muons have been calculated following
the procedure described in Ref. 4.

$$\phi_n = \sum_i K_i(A) \int E_o^{-\gamma_i(A)} P_n(E_o,A)dE_o$$

where $P_n(E_o,A)$ is the probability to sample n muons of a shower
resulting from the interaction of a primary with energy E_o, and mass
A, and the primary spectrum is described as a superposition of single
power spectra

$$\frac{dN}{dE_o} = \sum_i k_i(A)\, E_o^{-\gamma_i(A)} \qquad (i=p,\alpha,CNO,Mg,Fe)$$

Inputs to $P_n(E_0,A)$ come from the energy and radial muon distributions
calculated by Gaisser and Stanev (Ref. 5) for our experimental site. We
assume a value of -2.79 for the spectral index of proton and helium nuclei
as determined from our data and normalize the flux at 10 TeV to the JACEE
data. The spectral index for CNO and Mg groups is chosen slighty flatter
as suggested by direct measurements to which we refer for relative
normalization. The iron spectrum is normalized to a flux of $2.42\ 10^{-5}$
nuclei/(m²·sr·s·GeV/nucleon) at 100 GeV/nucleon, while its spectral index
is considered as a free parameter.

Beyond a rigidity R_c = 2 10^6 GeV/c, all spectra steepen to γ = 3.0.
The breaks for nuclei different from protons are at a total energy
$(A/2)R_c$.

Fig. 2 shows that the measured rates are well described by an iron
spectral index in the range 2.6 - 2.7.

This model describes very well both the all-nucleon flux in the range
10^{13} - 10^{14} eV and the all-particle flux between 10^{13} - 10^{16} eV
(see for example the compilation of Hillas in Ref. 6). Normalization
coefficients, slopes and breaking points or all components are summarized
in table 2.

CONCLUSION

We have determined a primary cosmic ray spectrum fitting both our
experimental multiple muon rates and the all-nucleon flux derived from
the single muon intensities underground.

In the frame of the interaction model developped by Gaisser, Elbert and
Stanev, we are able to reproduce NUSEX muon data with a primary
composition in which the iron spectrum is only slightly flatter than the
proton one.

This result rules out the popular idea that the primary composition
varies drastically with increasing energy, leading to the dominance of
heavier nuclei at energies 10^{15} - 10^{16} eV.

References

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[5] T.K. Gaisser and T. Stanev : private communication.
[6] A.M. Hillas : Proceedings of the Cosmic Ray Workshop, edited by T.K.
    Gaisser (University of Utah, 1983), p.16.

Figure Captions

Fig. 1 - Muon intensity underground at Mt. Blanc.
Fig. 2 - Comparison between experimental rates and the predictions of
         our model of primary composition for different values of the
         iron group spectral index.

Table 1

Rate of multiple muons

Multiplicity	# events	Time
1	20429	
2	211	
3	29	18946 hours
4	4	
5	2	
6	1	

Table 2

Group	K_i (m^{-2}s^{-1}sr^{-1}GeV^{-1})	γ_i	Points of change of slope, E(GeV)
P	$3.28 \ 10^4$	2.79	$2 \ 10^6$
He	$1.75 \ 10^4$	2.79	$4 \ 10^6$
CNO	$6.20 \ 10^3$	2.71	$1.4 \ 10^7$
Mg	$9.20 \ 10^3$	2.71	$2.6 \ 10^7$
Fe		2.6÷2.7	$5.2 \ 10^7$

OG 5.1-6

N85-34048
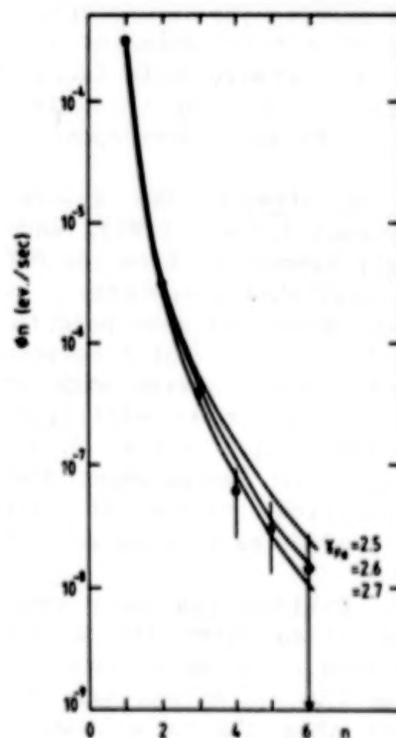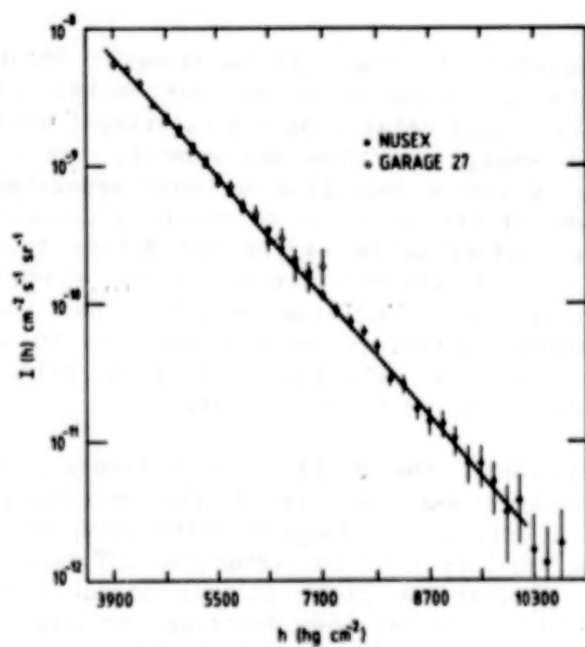
A NEW MEASUREMENT OF THE COSMIC RAY ENERGY SPECTRUM BETWEEN $3x10^{15}$ eV AND $3x10^{16}$ eV

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ABSTRACT

We give the results of a new Cerenkov photon density spectrum
measurement and present our derivation of the primary cosmic
ray energy spectrum for energies from $3x10^{15}$eV to $3x10^{16}$eV.

1. Introduction.   In a previous paper, Protheroe and Patterson[1]
examined the information available from various types of Cerenkov light
photon density spectrum measurements and proposed a conceptually simple
but powerful experiment.   From simulations, it was found that the photon
density spectrum of nearly vertical air showers observed by a system of
two detectors separated by 350 m was independent of nuclear mass
composition and depended only on the primary energy spectrum.   On the
other hand, a system of two detectors close together (or a single
detector) would be sensitive to the composition.   By making these two
measurements then, it is possible to determine the energy spectrum and
obtain information about composition.

In practice, the experiment is complicated by the necessity to
observe only near-vertical showers and to know the acceptance solid
angle of the system.   Either one severely collimates the detectors (or
uses mirrors) or one allows the detectors an unrestricted field of view
and selects the shower arrival directions by another technique, e.g. the
use of a third detector and timing coincidence.   Since the simulations
in ref. 1 were made for unshielded detectors we have used the latter
approach in order to avoid cutting out Cerenkov light produced in the
later stages of development.

2. Techniques.   Our system consisted of three 175 mm diameter 9623B
photomultipliers (PMT), each with a collimator to cut out background
light beyond 45° from the PMT axis.   Full details of the experiment will
be published elsewhere.   In the energy spectrum measurement, two of
these detectors were used to record photon densities and were separated
by 350 m.   The third detector was offset by 100 m to enable a coinci-
dence timing system with pre-determined pulse widths and delays from
each detector to restrict air shower arrival directions to a well
defined solid angle (0.32 sr) centred about the zenith.   For the
composition measurement the density detectors were moved to 100 m
separation, and the third detector to 31 m.   The pulse widths and delays
were adjusted to give an acceptance solid angle of 0.29 sr.

Calibrations were made throughout the night with a temperature
stabilised green LED pulser mounted near the rim of the mechanical
collimator to compensate for gain drifts. An absolute calibration of a
blue LED system was made in the laboratory by comparing the PMT output
with that due to a known flux of Cerenkov light photons produced by
single muons passing through BK7 glass and has been described by Gregory
et al[2].   This was used to calibrate the green pulsers in situ.

3. Observations. Initially, the fast PMT outputs were shaped by Ortec 485 main amplifiers, and the pulse heights were sampled and digitized. The system was tested at the Buckland Park field station and moved to a better observing site at Alice Springs for observations in May/June 1984. Alice Springs is at an elevation of 540 m and, for comparison with the simulations which were made for sea level, the detectors were tilted at 20° to the vertical in order to see showers at the same stages of development as in sea level observations. The pulse from the offset detector was appropriately delayed to tilt the acceptance solid angle for air showers by the same amount.

The results of this run for the May/June 1984 new moon period are shown in Fig. 1 by the open circles (details of the analysis are given below). With the rather slow electronics we were using, and the large field of view of the mechanical collimators, the results were subject to a fluctuating night sky noise component which became important below $\sim 3 \times 10^5$ photons m^{-2}. Estimates of the effect on the expected power law photon density spectra enabled approximate corrections to be made to these data and are indicated by the solid circles.
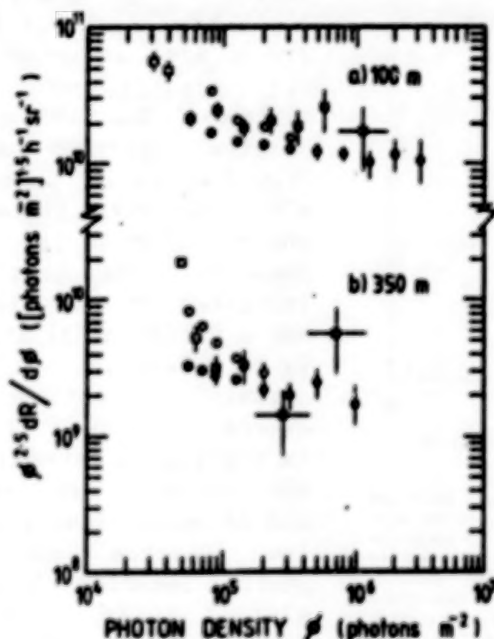
Fig. 1. Differential photon density spectra observed with (a) the 100 m system and (b) the 350 m system. Observations made at Alice Springs are indicated by open circles and are subject to biasses due to night sky noise below ~3x10⁵ photons m⁻². An approximate correction based on the characteristics of the system and an assumed night sky brightness of 6.4x10¹¹ photons m⁻² s⁻¹ sr⁻¹ has been made and these corrected data replotted as filled circles. Observations made subsequently at Woomera are indicated by filled squares and are subject to biasses due to night sky noise below ~5x10⁴ photons m⁻² (open squares).

Following the analysis of these observations, the electronics were redesigned around a LeCroy 2249SG Integrating ADC and the mechanical collimators were extended to reduce the sky background. The acceptance solid angle of the system for air showers was also reduced (to 0.082 sr and 0.11 sr for the 350 m and 100 m systems respectively) so that the mechanical collimators did not obstruct any Cerenkov light from those air showers accepted. The net result of this was to reduce the night sky noise, thus allowing reliable measurements to be made to lower photon densities. The modified system was operated at Woomera (altitude 166 m, tilted at 10° to the zenith) during the March 1985 new moon period. The results from this run are shown by the solid squares in Fig. 1 and are in excellent agreement with earlier runs at high photon densities. At low photon densities, the results are consistent with the corrected Alice Springs data except for the lowest two points (plotted as open squares) which are affected by night sky noise.

4. <u>Data Analysis.</u>   For each event, the digitizer outputs from the two density measuring detectors were read by the computer and converted to photon densities using the calibration results. The lower of the photon densities was binned in photon density on a logarithmic scale. During the readout and analysis, the system was automatically inhibited and was de-inhibited by the computer on completion of its analysis.   This resulted in a dead-time of ~0.3 s per event. An internal clock recorded the live time. Although each event is accurately calibrated, the discriminator threshold varied during the run due to gain drifts and changing night sky brightness within the field of view. For each run, only events with photon densities well above the discriminator threshold were included in the final analysis.   The acceptance solid angle was calculated from the pre-set discriminator output pulse widths and delays.   Thus, for each run the exposure (live time x solid angle) and minimum acceptable photon density were determined.   The data from separate runs were then combined to obtain the results shown in Fig. 1.   Our final result based on those data of Fig. 1 which were unaffected by night sky noise are replotted in Fig. 2.
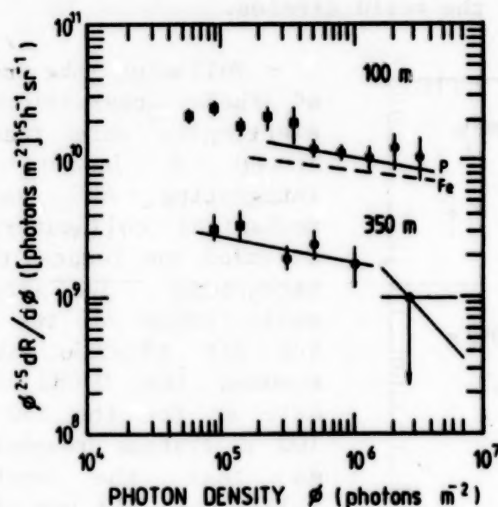
Fig. 2. Photon density spectrum data from Fig. 1 which are not subject to biasses due to night sky noise. Points with large error bars are also omitted for clarity. A power-law fit to the 350 m data is plotted. Upper limits to power law spectra above 1.6×10^6 photons m^{-2} are also plotted. Expected 100 m photon density spectra based on the cosmic ray energy spectrum obtained from the 350 m data are plotted for two extreme assumptions about the nuclear mass composition.

5. <u>Discussion.</u>   We can derive the primary cosmic ray energy spectrum from the 350 m data independently of the nuclear mass composition.   The 350 m photon density spectrum data of Fig. 2 up to 10^6 photons m^{-2} are well fitted by a power law in photon density.   The best fit is indicated in the figure and has a differential index of $\gamma_\phi = 2.7 \pm 0.2$.   Above 1.6×10^6 photons m^{-2}, no events were recorded, indicating a steepening in the cosmic ray spectrum, and 1σ upper limits to power law spectra above this photon density have been plotted in Fig. 2 for γ_ϕ ranging from 2.5 to 3.5.   Using Fig. 9(a) of ref. 1, which relates γ_ϕ to γ_E for different spacings, this corresponds to a spectral index $\gamma_E = 2.72 \pm 0.2$ for the cosmic rays.   The cosmic ray energy spectrum in the energy range $3 \times 10^{15} - 3 \times 10^{16}$ eV (corresponding to $10^5 - 10^6$ photons m^{-2} for the 350 m system) may then be obtained directly with the aid of Figs. 8 and 9(b) of ref. 1 which relate photon density to primary energy and the absolute fluxes. The result is shown in Fig. 3 where it is compared with previous measurements of the cosmic ray energy spectrum.   Our result is consistent with the extrapolation to lower energies of the Haverah Park data if there is a steepening of the spectrum at $\sim 3 \times 10^{16}$ eV. Comparison with balloon and satellite data at
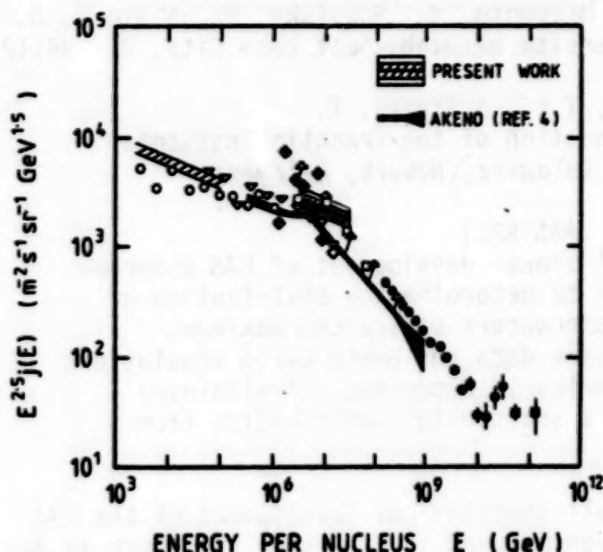
Fig. 3 Primary cosmic ray energy spectrum measurements (see ref. 3 for key to data). Our result at $3\times10^{15}-3\times10^{16}$ eV is indicated and is subject to statistical and systematic errors each of about 10%.

lower energies would indicate the presence of a "kneecap". The Akeno data also indicate the presence of a kneecap but at a factor of ~3 to 5 lower energy.

For the cosmic ray energy spectrum we derived from the 350 m data, we can predict the photon density spectrum for the 100 m system assuming different nuclear mass compositions with no other adjustments being made. This has been done for two extreme assumptions, 100% protons or 100% Fe-nuclei, using simulation results similar to those described in ref. 1 but appropriate to the 100 m system. The expected 100 m spectra are plotted in Fig. 2 for comparison with the data. (Note that for the 100 m system, $3\times10^{15}-3\times10^{16}$ eV corresponds to higher photon densities than for the 350 m system.) Unfortunately, with the detectors moved apart to 100 m some sensitivity to composition is lost (all sensitivity is lost for 350 m). Also, because of the relatively low power law index of the cosmic ray spectrum in this energy range the two curves are rather close together. Nevertheless, the data appear to favour a relatively light composition although a heavy composition is not ruled out. More data would be required to resolve this question. Whatever the composition, however, provided it remains unchanged down to ~10^{15} eV, the 100 m data would indicate that the cosmic ray spectrum we derived between 3×10^{15} and 3×10^{16}eV continues unchanged down to ~10^{15} eV.

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STUDY OF THE COMPOSITION OF COSMIC RAYS WITH ENERGY .7<E<3 EeV

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ABSTRACT
The longitudinal shower development of EAS observed
in the Fly's Eye is used to determine the distribution of
X_{max}, the depth in the atmosphere of the EAS maximum.
Work in progress to compare data and Monte Carlo simulations
of proton and iron primaries is described. Preliminary
evidence is in favor of a substantial contribution from
light primaries.

1. Introduction.
The overall longitudinal development of the EAS
detected by the Fly's Eye[1] can be used to determine the depth in the
atmosphere in gm/cm^2 of the EAS maximum X_{max}. The distribution in X_{max}
is in principle sensitive to the composition of the primary particles
since iron nuclei and protons will give rise to X_{max} distributions that
peak at shallower and deeper depths and have narrower and wider widths,
respectively. It also follows that a mixed composition will have a
broader X_{max} distribution than any single source.

In what follows, we discuss the reconstruction of longitudinal
shower profiles and the systematics of determining X_{max} distributions
and then discuss work in progress on Monte Carlo simulations, which
include the details of the Fly's Eye acceptance, for pure protons,
iron, and a mixed composition.

2. Shower Size Measurement.
A fit to the relative time of arrival
of light to succeeding phototubes in the event-detector plane yields
R_p, the impact parameter of the shower to the detector, and the zenith
and azimuthal angles of the EAS. Measured values of optical gathering
power, efficiencies and electronic gains and pedestals are used to
convert photoelectron yields into apparent brightness, i.e., numbers of
photons arriving at the detector from the source. This can be converted
into intrinsic source fluorescent brightness after correcting for: (a)
directly produced Cerenkov light beamed in the direction of the detector;
(b) Cerenkov light scattered in the direction of the detector due to
Rayleigh and Mie scattering; and (c) atmospheric attenuation of light.
The details of these corrections are described in reference 1. The
intrinsic fluorescence brightness can be translated directly into a
shower size using the known nitrogen fluorescence efficiency.

The Cerenkov light production model, and in particular, the
dependence of the Cerenkov light intensity on emission angle has been
checked by using a sample of events seen by both Fly's Eye I and Fly's
Eye II, a smaller station situated 3.3 km from Fly's Eye I. We find
good consistency in size estimates of sections of EAS viewed

simultaneously at different emission angles by the two eyes.

The size versus depth distributions are fitted with a Gaussian form and the X_{max} and energy of the event determined(1). The Gaussian form fits most showers well. Figure 1 shows a typical shower profile.
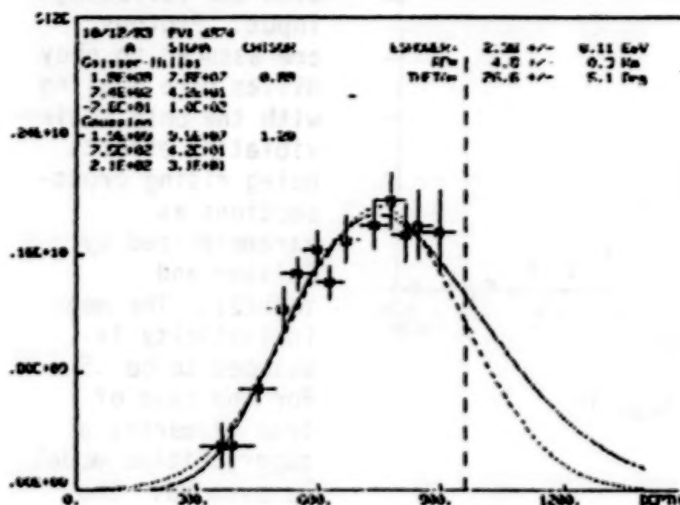
Figure 1. Typical Longitudinal Shower Profile

3. Systematics of Shower Maximum Distributions The absolute depth of X_{max} is the parameter most sensitive to systematic errors of any that we measure. Symmetric random errors in the zenith angle, θ_z, result in non-symmetric errors in X_{max}. Symmetric errors in R_p also yield non-symmetric errors in X_{max} because of the exponential atmospheric density distribution. There is also an intrinsic correlation between X_{max} and the shower energy. Showers whose reconstruction err to smaller R_p and larger θ_z will have systematically deeper X_{max} and smaller estimated energy while errors that lead to larger R_p and smaller θ_z yield smaller X_{max} and larger energy estimates. This is a direct consequence of random errors and the exponential nature of the atmosphere. Any additional systematic bias in θ_z or R_p will shift the X_{max} distributions accordingly.

To reduce these effects to a minimum, we consider events that are very well reconstructed, with $R_p > 2.0$ km, projected track length $>50°$, $SR_p/R_p < .1$, $S\theta_z < 10°$ and relative uncertainties in Gaussian width, X_{max}, and energy of $< .4$. These cuts also have the effect of reducing the Cerenkov subtractions to a level where 50% variation in the Cerenkov light model parameters do not significantly affect the X_{max} distributions. Since any residual reconstruction bias will affect data near the tails of the energy distribution, we cut on $.7 < E < 3$ EeV, around the maximum of our energy acceptance. We believe residual systematic effects in this data sample will produce less than a ± 50 gm/cm^2 shift in the average X_{max}. We note that the width of the X_{max} distribution is much less sensitive to systematic errors. We estimate the systematic error in the width to be ± 10 gm/cm^2. The resultant distribution in X_{max} is shown in Figure 2. The average X_{max} for this sample is 730 ± 60 gm/cm^2 while the width (standard deviation) is 120 ± 40 gm/cm^2.

$<X>=(7.288 \leftarrow 56)E-1$ $SD=(1163 \leftarrow 39)E-1$

GAUS XMAX
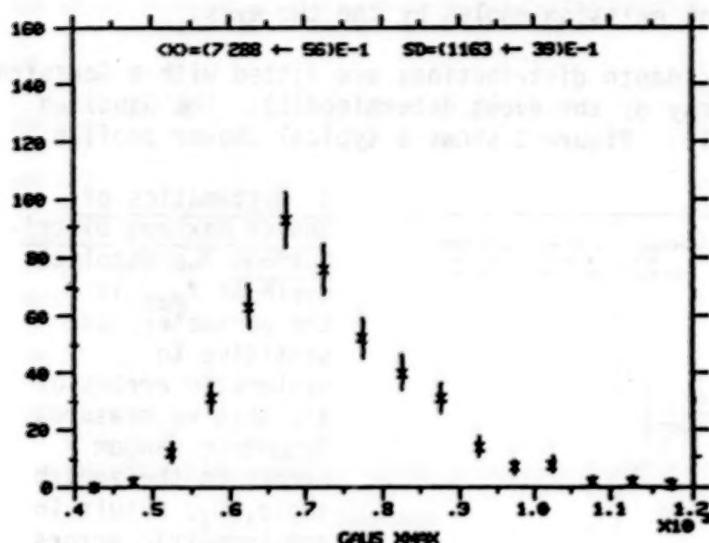
Figure 2. Distributions of X_{max} in gm/cm^2.

4. Monte Carlo Generation

Proton and iron induced showers are generated in a Monte Carlo program with the following input. Protons are assumed to obey Hillas pure scaling with the only scale violating effects being rising cross-sections as parameterized by Gaisser and Yodh(2). The mean inelasticity is assumed to be .5. For the case of iron primaries a superposition model is assumed. The Monte Carlo follows hardons and electromagnetic particles down to 1/30th of the primary energy after which parameterizations of shower development are used. We use these showers to predict the number of photoelectrons and relative time delays observed in the detector and generate fake events which are then passed thru the same reconstruction and analysis programs as the real data. This work is in progress but preliminary indications are that the depth of maximum distribution for heavies is substrantially narrower than that for protons. It is important to note that comparing the observed X_{max} distributions to theoretical predictions without taking into account the details of detector response can lead to misleading conclusions.

5. Conclusions.
Although we are not yet ready to quote quantitative comparisions between the data and Monte Carlo simulations, preliminary evidence based on comparisons of the widths of the X_{max} distribution to Monte Carlo is in favor of a substantial contribution from light primaries to the cosmic ray composition at these energies. Detailed comparisons will be forthcoming.

6. Acknowledgements.
We gratefully acknowledge the United States National Science Foundation for its generous support of this work under grant PHY8201089.

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THE MUON CONTENT OF EAS AS A FUNCTION OF PRIMARY ENERGY

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1. Introduction At Haverah Park the muon content of EAS has been
measured over the wide primary energy range 10^{16} to 10^{20} eV. At the
Bangalore Conference it was reported (Blake et al, 1983) that the
relative muon content of EAS decreases smoothly [$\sim \rho(600 \text{ m})^{0.94}$] over
the energy range 10^{17} - 10^{19} eV and therefore concluded that the
primary cosmic ray flux has a constant mass composition over this
range. In the same paper (on the basis of a preliminary analysis)
it was also reported that an apparent significant change in the
power index occurs below 10^{17} eV [$\rho_c(250 \text{ m})^{0.78}$]. Such a change
would indicate a significant change in primary mass composition in
this range.

Further analysis confirms the earlier conclusions concerning EAS of
energy $\geq 10^{17}$ eV. However post-Bangalore analysis of data in the
10^{16} - 10^{17} eV range revealed a previously overlooked selection bias
in the Bangalore data set. This paper presents the full analysis of
the complete data set in the energy range 10^{16} - 10^{17} eV with the
selection bias eliminated.

2. Methods Three 10 m² muon detectors ($\sim$ 400 MeV threshold) were
operated in conjunction with the deep water Cerenkov tank array
(operated by the University of Leeds EAS group) at the Haverah Park
site. Two of these muon detectors were immediately adjacent to
large area water Cerenkov detectors, enabling a direct measurement
of the ratio of the muon response to the water Cerenkov response
(ρ_μ/ρ_c) to be made. The water Cerenkov response (ρ_c) is dominated
at low core distances by the electromagnetic response. The directly
measured ratio (ρ_μ/ρ_c) has the advantage of not being very sensitive
to EAS parameters and therefore not sensitive to any inaccuracies in
determining these parameters.

3. Results (10^{16} - 10^{17} eV) The basic problem in establishing an
accurate determination of the muon content over a large primary
energy range arises from the measurement technique. Inevitably in
most arrays (including the Haverah Park array) the core distance
range covered is a strong function of primary energy (or shower
size). The ratio (ρ_μ/ρ_c) itself will be a function of core distance
and thus direct determination of ρ_μ/ρ_c at a specific core distance
is limited to a small range of primary energies. If a relationship
of the form $\rho_\mu = k \rho_c{}^\alpha$ is adopted, k can normally be regarded as
constant at a particular core distance (R); the power index
(normally 0.94) may be a function of core distance and shower size.
A core distance dependence would arise if the lateral density
distributions of ρ_μ or ρ_c significantly change with shower size.
Measurements indicate that the lateral distribution of ρ_μ is
unchanging at energies > 10^{16} eV. However the lateral distribution
function of the electromagnetic component (and therefore ρ_c) does

show some change as the electromagnetic cascade maximum penetrates more deeply into the atmosphere as E_p increases. Thus in determining the exponent 'α' it is sensible to limit the core distance range to as small a core distance interval as is statistically feasible.

The available experimental data were divided into three overlapping intervals of core distance:- 50 m $\leq$ R $\leq$ 150 m; 100 m $\leq$ R $\leq$ 200 m; and 150 m $\leq$ R $\leq$ 250 m. The data were further subdivided into four sec θ intervals 1 → 1.1 → 1.2 → 1.3 → 1.4 and six shower 'log' size intervals. The data were then used to calculate the mean measured muon and water Cerenkov responses at R = 100 m, 150 m and 200 m. The results for 1.0 < sec θ < 1.1 are displayed in Table 1 & Figure 1.
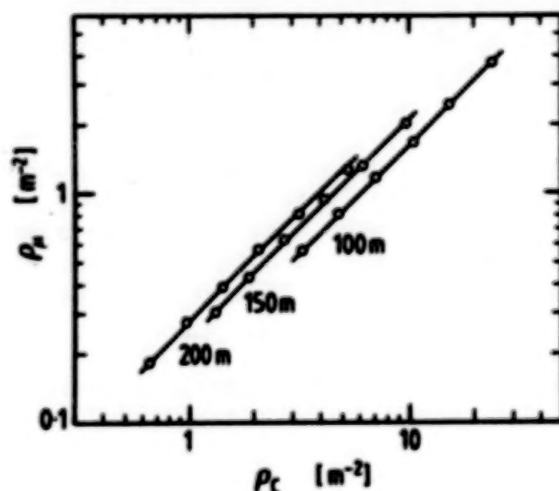
Clearly the ρ_μ/ρ_c ratios change smoothly over this decade of primary energy.

Table 2 shows the best fit values of α obtained from linear regression fits on the relationship $\rho_\mu = k\rho_c^\alpha$ for all the R and sec θ intervals.

FIGURE 1 Measured ρ_μ versus measured ρ_c at three specific core distances.

R	$\frac{/m^2}{\rho_{150}}$	N	$\frac{/m^2}{\overline{\rho}_\mu}$	$\pm \Delta\rho_\mu$	$\frac{/m^2}{\overline{\rho}_c}$	$(\overline{\rho}_\mu/\overline{\rho}_c)$	$\pm \Delta\rho_\mu/\rho_c$
100 m	1.23	2466	0.560	0.011	3.306	0.169	0.003
	1.81	2362	0.805	0.017	4.833	0.167	0.004
	2.66	1793	1.188	0.028	7.091	0.168	0.004
	3.90	1106	1.664	0.030	10.586	0.157	0.003
	5.73	529	2.430	0.11	15.841	0.154	0.007
	8.41	234	3.764	0.25	24.209	0.155	0.010
150 m	1.23	2040	0.306	0.007	1.333	0.230	0.005
	1.81	2303	0.432	0.009	1.915	0.226	0.005
	2.66	2065	0.634	0.014	2.773	0.229	0.005
	3.90	1397	0.930	0.025	4.119	0.226	0.006
	5.73	820	1.301	0.045	6.239	0.209	0.007
	8.41	378	2.025	0.104	9.907	0.205	0.010
200 m	1.23	904	0.179	0.006	0.648	0.276	0.009
	1.81	1335	0.272	0.007	0.979	0.278	0.007
	2.66	1540	0.368	0.010	1.438	0.268	0.007
	3.90	1287	0.584	0.016	2.098	0.278	0.008
	5.73	886	0.809	0.027	3.255	0.249	0.008
	8.41	470	1.255	0.058	5.141	0.244	0.011

<u>Table 1</u> (previous page) Mean muon ($\bar{\rho}_\mu$) and water Cerenkov $\bar{\rho}_c$ densities as a function of core distance (R) and shower size (ρ_{150}) - $1.0 \leq \sec\theta \leq 1.1$.
[ρ_{150} is the water Cerenkov response in vertical equivalent muons at 150 m from the EAS axis. N = no. of EAS used in the analysis]

R	Secθ 1.0 - 1.1	Secθ 1.1 - 1.2	Secθ 1.2 - 1.3	Secθ 1.3 - 1.4
100 m	0.95(0.01)	0.92(0.02)	0.90(0.02)	1.01(0.04)
150 m	0.94(0.02)	0.95(0.02)	0.99(0.02)	0.99(0.06)
200 m	0.94(0.02)	0.94(0.03)	0.93(0.08)	0.90(0.05)

<u>Table 2</u> Values of α in the relationship $\rho_\mu = k\rho_c^\alpha$ as a function of R and θ.

Clearly, at least for low zenith angles, an average value of $\alpha = 0.94$ fits the data well in the core distance range 50 m → 250 m and over the primary energy range 1.6×10^{16} eV < E_p < 1.6×10^{17} eV.

4. <u>Muon Content $10^{16} - 10^{19}$ eV</u> Data acquired in the primary energy range $10^{17} - 10^{18}$ eV from the infilled 500 m detector array at Haverah Park enables ρ_μ (200 m) and ρ_c (200 m) to be determined for the decade of energy above 10^{17} eV. The results are plotted in Figure 2 which shows the complete data from $10^{16} - 10^{18}$ eV.
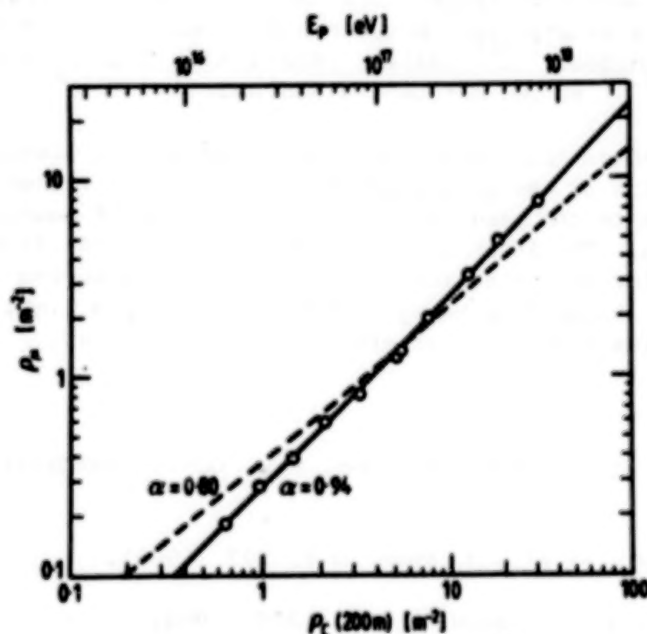
FIGURE 2 Measured ρ_μ versus ρ_c at 200 m over energy range approximately $10^{16} - 10^{18}$ eV.

It is clear that a relationship of the form $\rho_\mu(200\ m) = \rho_c(200\ m)^{0.94}$ fits smoothly and well over these two decades of energy. This implies a smooth gradual change in the height of the electromagnetic cascade maximum throughout these two decades.

Thus the muon data yields strong evidence that there is no marked primary mass change occurring in the 10^{16} to 10^{17} eV region as has been suggested. If there is a significant change in primary mass, as suggested by Chantler et al (1983), then the muon density would be approximately 50% higher at 10^{16} eV than is measured leading to a value of $\alpha \sim 0.8$ [Blake et al, 1983]. Such a low value of α is clearly incompatible with the measured data (see Figure 2).

Comparison of the 10^{17} to 10^{18} eV decade with energies above 10^{18} eV has been carried out at a core distance of R = 600 m. In this region the data and conclusions remain unchanged since Blake et al (1983). Again the observations yield a smooth and normal change in muon content in the range 10^{17} eV to 10^{18} eV, implying no significant primary mass change over the energy range.

5. **Discussion and Conclusions** The results presented above lead to the conclusion that the muon content of EAS (relative to the water Cerenkov response) decreases smoothly in a constant manner at primary energies above 10^{16} eV and therefore suggest a constant primary mass composition in this energy region. A direct and constant relationship between the primary mass energy (E_p) and the water Cerenkov response $\rho_c(R)$ is assumed. The water Cerenkov response at 500 m core distance, $\rho(500)$, [or at 600 m, $\rho(600)$] is used as the shower size parameter at Haverah Park for energies > 10^{17} eV and the relationship between $\rho(500)$ and E_p is of the form $E_p = 3.87 \times 10^{17} [\rho(500)]^{1.018}$ [HILLAS, Model A]. Thus $\rho_\mu \propto \rho_c^{0.94}$ implies $\rho_\mu \propto E_p^{0.92}$ at 500 m from the EAS axis.

Assuming therefore that this result does indicate a constant primary mass composition at energies greater than 10^{16} eV it does give strong support to the results from other studies of muons in EAS at these energies. The Akeno group (Nagano et al, 1984) find that the size spectra for both electrons and muons are unchanging above 10^{16} eV. Thus any change from heavy primary nuclei to a light mass composition flux must occur at energies below 10^{16} eV.

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N85-34051

ON THE POSSIBILITY OF DETERMINING THE AVERAGE MASS COMPOSITION NEAR 10^{14} eV THROUGH THE SOLAR MAGNETIC FIELD

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ABSTRACT

The discovery of primary U.H.E. gamma-rays has spawned plans for a new generation of air shower experiments with unprecedented directional resolution ($\leq 1^0$). Such accuracy permits observation of a cosmic ray "shadow" due to the solar (and lunar) disc. Particle trajectory simulations through models of the large scale solar magnetic field have been performed. The shadow is apparent above 10^{15} eV for all cosmic ray charges $|Z| < 26$; whereas, at lower energies, trajectories close to the Sun are bent sufficiently for this shadow to be lost. The onset of the shadow is rigidity dependent, and occurs at an energy per nucleus of $\sim Z \times 10^{13}$ eV. The possibility of determining the average mass composition near 10^{14} eV from 1 year's observation at a mountain altitude array is investigated.

1. **Introduction.** A challenge, proposed as a comment by Clark [1], to observe a narrow angle shadow in the cosmic ray flux due to solar and lunar absorption has not been taken up by air shower experiments. The reason is clear; for a statistically significant (> 3σ) deficit from the Sun or Moon, the whole-sky event number to be registered (assuming 1 sr exposure) is $\sim 3.10^6 \times d\theta^2/f$ ($d\theta$ = semi angle of directional resolution (degs); $f = 0.1$, is the duty cycle for observing the Sun or Moon). Thus, with current resolution (typically $d\theta \sim 2°$) $\sim 10^8$ events are required. However, the discovery of primary U.H.E. γ-rays has spawned plans for a new generation of air shower arrays with unprecedented directional resolution [2,3]. It may be possible [3] to obtain $d\theta \sim 0.5°$, so that with a reasonable trigger rate of ~ 0.2 sec^{-1}, observation of cosmic ray shadows would be possible in 1 year's integration time.

The Moon acts as a 'passive absorber' at all air shower rigidities (> 10^{13} eV/nucleus) since the effect of geomagnetic fields are insignificant above TeV energies. The directional resolution of air shower arrays is notoriously difficult to estimate; the lack of calibration point sources has resulted in reliance on calculations of the cumulative effects of numerous experimental limitations. Consequently, observation of the Moon's shadow will greatly aid the search for potential U.H.E. sources.

That the Sun is an 'active absorber' (i.e., the shadow is rigidity dependent) in the air shower regime can be seen simply. Above an energy where the particles' gyroradii are comparable to the solar radius, a narrow angle shadow cannot be observed. Putting $B \sim 1G$, $r_g \sim$

7×10^{10} cm and adopting the high energy limit (rigidity α total energy/z) the loss of a shadow is expected for energies of order $z \times 2.10^{13}$ eV. If the rigidity dependence can be modelled accurately, we have the possibility of using the large scale solar magnetic field as a crude magnetic spectrometer [4].

Here, we consider a simple model for the field within 1 A.U. and calculate trajectories of particles with arrival directions within 1° of the Sun. The discriminating power of the technique for charge resolution near 10^{14} eV is estimated, and limitations due to field approximations are discussed.

2. Method. Application of the potential source surface technique [5], and the 'garden-hose' field topology [6] have been very successful in interpreting the measured ecliptic field topology near 1 A.U. [7]. We consider a simple potential source surface at 2 r_0, and extend the field to 1 A.U. using Parker's equations [6] with $\Omega = 2.7 \times 10^{-6}$ and $V = 400$ Km s^{-1}. Fluctuations are imposed by adding a component of equal magnitude at an angle of $|d\theta|r.m.s. = 20°$ over a scale length of 1 r_0. A 4 sector structure is also imposed, with the field direction reversing across the sector boundary.

Particle trajectories are computed by step-wise numerical integration of the equations of motion, with the particle's constant velocity as a constraint. The calculations have been checked by examining the circular orbits of particles fired perpendicular to uniform fields. The step-length is the smaller of (a) 10^{-2} x gyroradius or (b) 10^{-2} r_0. A step-length 10 x smaller results in negligible trajectory differences. Negatively charged particles are fired back from the Earth within a ~ 1° cone centered on the Sun. Trajectories are followed until they either intercept or miss the solar surface. Two thousand five hundred trajectories are computed over the acceptance cone for each field configuration and rigidity.

In Figure 1, the proportion of events within the cone which intercept the Sun is shown as a function of particle total energy for proton and Fe primaries (Model II). For comparison, the results for a simple dipole field, with no fluctuations, are also shown (Model I).

3. Discussion. It must be emphasized that: (1) the 'saturation obscuration' (in this case 18%) and zero obscuration are model independent, depending solely on the air shower array's field of view (in this case $d\theta = 0.6°$); (2) the separation of nuclear species is model independent, being α Z; (3) as indicated in Figure 1, the energy at which the shadow appears is very model dependent. In particular, the magnitude and scale length of the field within ~ 5r_0 are of paramount importance. Model II may considerably underestimate the field magnitude within 2r_0, but overestimates the scale length. We believe there is a factor of ~ 5 uncertainty in the energy at which the shadow appears, and that Model II is a reasonable lower limit to the transition energy.

In Figure 1 the rise-energy (over which the obscuration rises from 10 to 50%), $E_{50\%}$, is ~ Z x 5 TeV, and $E_{90\%}$ ~ Z x 18 TeV (or, as a fraction of E_{50}: ΔE_{50} ~ 0.49, ΔE_{90} ~ 1.9). These two parameters would be severely underestimated (and hence the power to discriminate between composition models curtailed) if (a) the field of view was
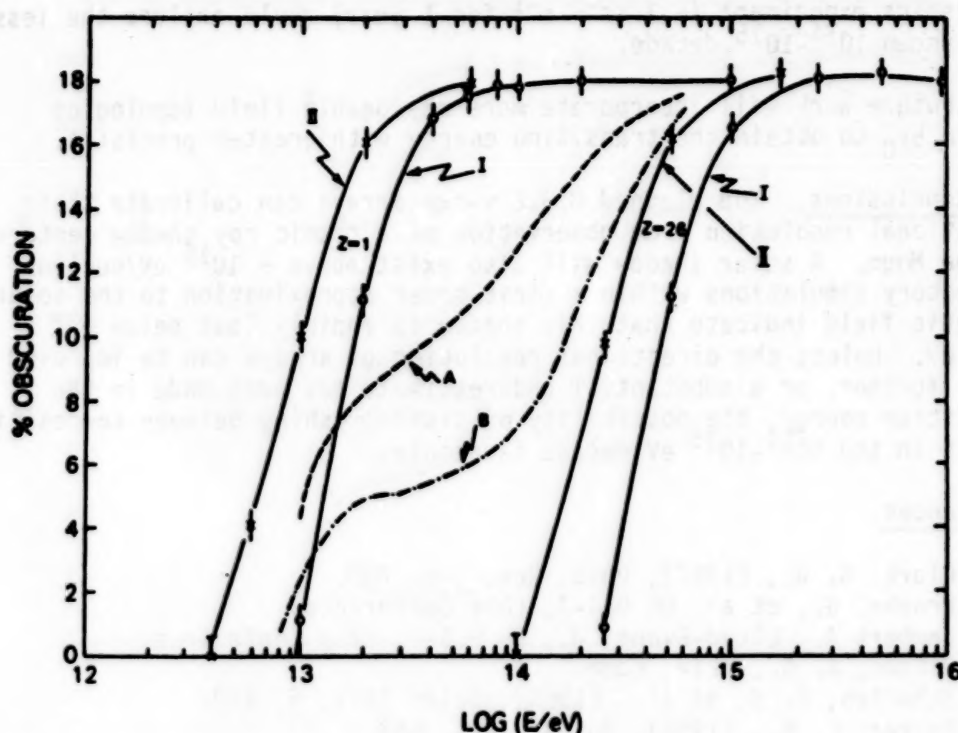
Fig. 1. The appearance of a solar shadow within a 1.2° acceptance cone for protons and Fe nuclei for field representations I, II (see text). The dotted curves show the resulting transition for two simple composition models (see text).

underestimated or (b) large, unknown, variations in the average magnetic field strength occurred over a 1 year timescale. Possibility (a) is removed by normalizing the saturation obscuration to that for the Moon (see Section 1). The global magnetic field varies by ~ x 3 near the photosphere through the solar cycle and by 20-40% at 1 A.U [8]. Thus, long term monitoring of the photospheric fields, currently undertaken, is required to minimize the effects of (b).

The values ΔE_{50}, ΔE_{90} can be compared to those calculated by a simple impact parameter approach [9]. Averaging over all impact parameters within the field of view which penetrate the solar surface, we obtain $\Delta E_{50} \approx 0.45$, $\Delta E_{90} \approx 1.5$, in close agreement with those determined above.

To investigate the mass resolution of the technique, we show the predicted transition for two models of the mass composition in the 10^{13} eV to 10^{15} eV decades in Figure 1. Curve (B) has an energy dependent, fractional composition (p: α: CNO: 10 < Z < 20: Fe) of (40-15 log (E/TeV): 15: 15: 15: 15 + 15 log(E/TeV) %), and curve (A) of (45-2.5 log(E/TeV): 15: 15: 15: 10 + 2.5 log(E/TeV) %). These models, though simple, are chosen to represent extreme bounds on the controversial variation in compositon (see, for example refs. [10], [11]). The energy window for composition discrimination lies near 10^{14} eV, and a statistical precision of <3% is required to choose between models. We conclude that this technique only becomes attractive if the transition energy has been underestimated by >x 5; then a high

statistics experiment (~ 1 sr^{-1} s^{-1} for 1 year) could explore the less well known 10^{14}-10^{15} decade.

Future work will incorporate more reasonable field topologies within $5r_0$ to obtain the transition energy with greater precision.

4. Conclusions. The planned U.H.E γ-ray arrays can calibrate their directional resolution from observation of a cosmic ray shadow centered on the Moon. A solar shadow will also exist above $\sim 10^{15}$ eV/nucleus. Trajectory simulations within a first order approximation to the solar magnetic field indicate that this shadow is rapidly lost below $\sim Z \times 10^{13}$ eV. Unless the directional resolution of arrays can be improved still further, or a substantial underestimate has been made in the transition energy, the possibility of distinguishing between composition models in the 10^{14}-10^{15} eV decade is remote.

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A New method to determine the Chemical Composition of the Cosmic Rays beyond 10^{15} eV

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abstract

The chemical composition of primary cosmic rays beyond 10^{15} eV could not be measured by the direct method. Here I would like to propose more sensitive method to determine the chemical composition. The idea has been checked by the simulation and compared with the exsisting data concerning on $N_e - N_\mu$ and $N_e - N_\gamma$.

The simulation will be also cmpared with the experimental results coming from ANI experiment in a near future.

Cosmic Ray Composition between 10^{15} to 10^{17} eV obtained by Air Shower Experiments

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abstract

Based on the air shower data, the chemical composition of the primary cosmic rays in the energy range 10^{15}-10^{17}eV has been obtained.   The method is nased on a well known N_e-N_μ and N_e-N_γ.   Our simulation is calibrated by the CERN SPS $p\bar{p}$ collider results and very reliable.

1. Introduction and Model

When the first $p\bar{p}$ collider results from CERN has reported in the end of 1981, we have started a Monte Carlo calculation with the use of the data on the nuclear nuclear interaction. The first result has been already published in a proceeding of the Bagalore conference and the simulation model is described in detail therin[1], however, here we describe briefly the simulation model : $\langle n_s \rangle \propto E_0^{1/6}$, $\sigma_{tot} \propto (\ln\sqrt{s})^2$, $K/\pi \sim 0.15$, $\langle P_T \rangle \sim 0.4$ GeV/c and no energy dependency.   The effect of geo-magnetic field and the scattering in the air have been taken account of.

2. Transition Curve

The transition curve of the electron number N_e is shown in Fig. 1 as a function of the altitude. ● and X represent the proton and iron primaries respectively with the same incident energy $E_0 = 2 \times 10^{16}$eV.   The error bar implies the region of 90% air shower involved, while ● and X represent the mean value.

Fig. 1 Transition curve for proton(o) and iron(X)
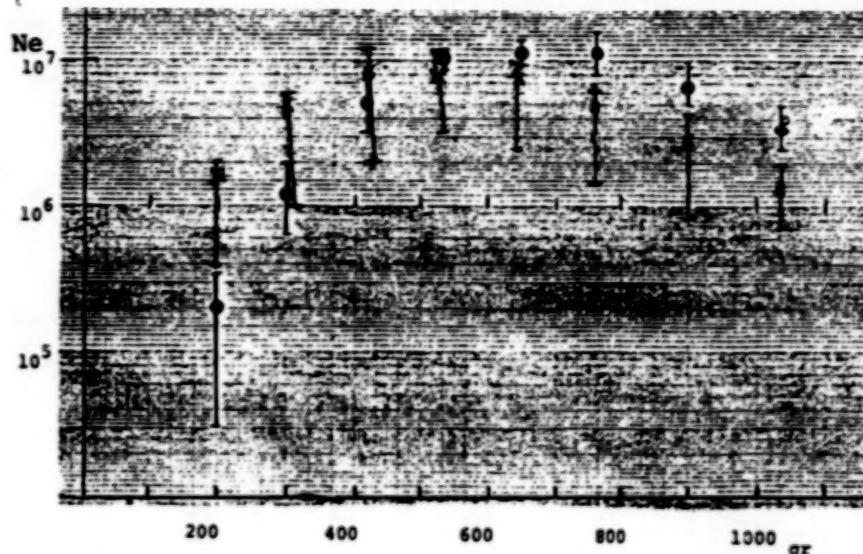
3. N_e-N_μ plot and Trigger Bias

It is interesting to compare present result with the previous calculation by Jōgo [2]. Our result of proton(----) primary fits well with the result based on CKP model for proton promaries rather than sacling model with iron primaries calculated by Jōgo. However we must take account of the trigger bias involved in the data taking. As shown in Fig. 3, even if the composition of primary cosmic rays could be 90% iron(x) nad 10% proton(●) beyond 10^{15}eV, it is identified as proton dominant by the N_e trigger. To avoid such a misunderstanding, N_μ trigger is preffered.
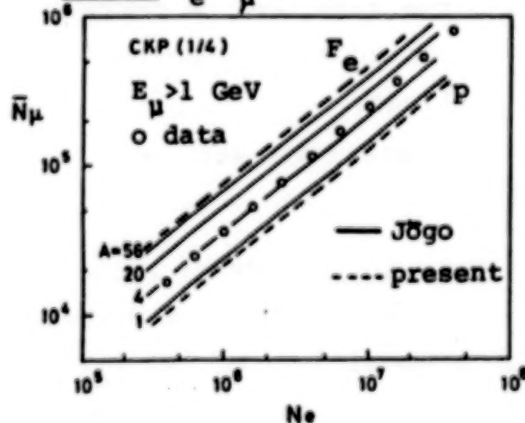
Fig. 2 N_e-N_μ plot

Fig. 3 Trigger bias (●)P,(x)F_e
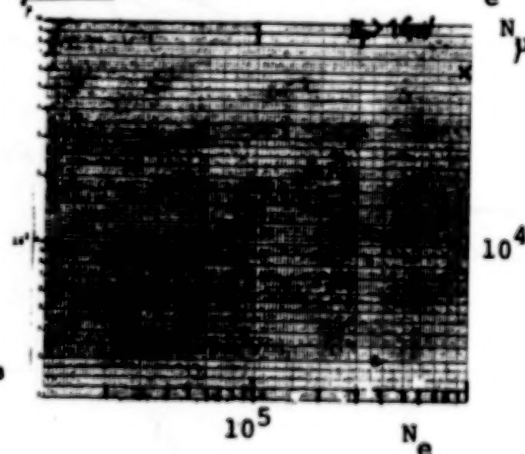
4. N_μ-N_e Trigger Data

Fig. 4 represents N_e-N_μ contour plot by N_e trigger.
In a range of $N_e \gtrsim 10^7$, no trigger bias is observed even if the
data have been taken by $\bar{N}_e$ trigger[3].

In the same N_e-N_μ plot of Fig.4, we draw the line with
the same incident energy for various kind of primaries (Fig. 5).
The highest peak of the contour corresponds to the size s=1.1.
The corresponding size for each primary is s=1.0-1.2 for proton
, s=1.2-1.3 for He, s=1.3-1.4 for CNO, and s=1.4-1.5 for iron
in 900 grams(Akeno).
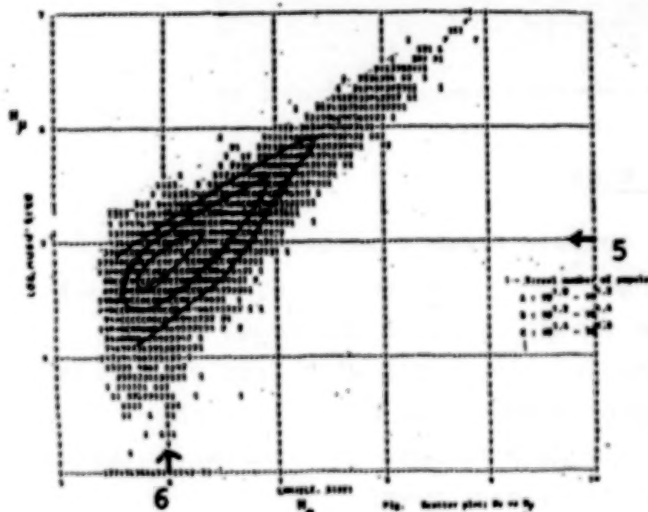
Fig. 4 N_μ-N_e plot

a,b,c corresponds the
number of events :
a : $10^{1.0}$-$10^{1.2}$
b : $10^{1.2}$-$10^{1.4}$
c : $10^{1.4}$-$10^{1.6}$
(data from Ref. 2)
real number means real
population

Fig. 5 Contour plot
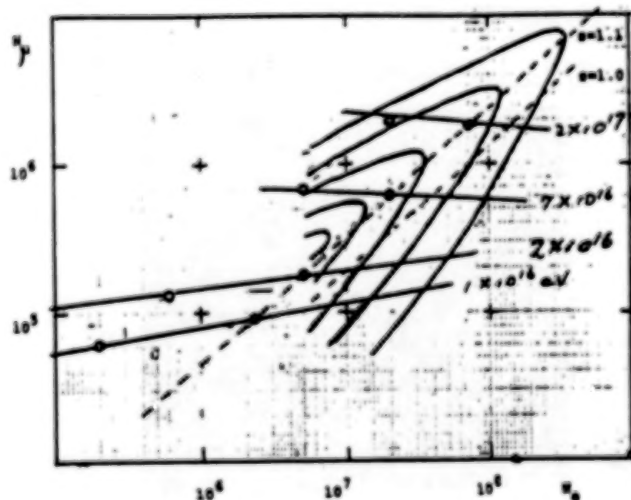
the same incident energy
line is drawn by line.
the same age is repre-
sented by the dotted
lines.

(data from Ref. 3)

Note added: above logic
holds even if the primary
composition is 90% F_e +
10 % P. We assumed peak
corresponds to proton.

Fig. 7

events

INTRODUCTION TO THE GALACTIC COSMIC RADIATION

Chicago
data

JACEE
results

Present
analysis

$2 \times 10^{16} eV$

$7 \times 10^{16} eV$

$2 \times 10^{17} eV$

P He C N O Fe   P He C N O Fe   P He C N O Fe
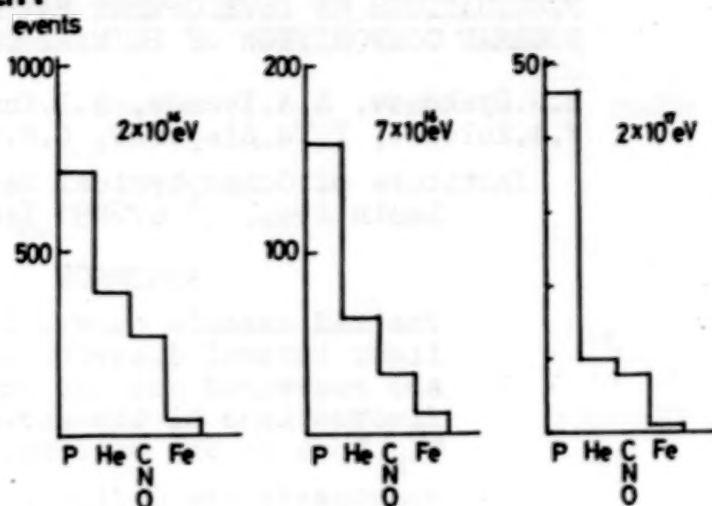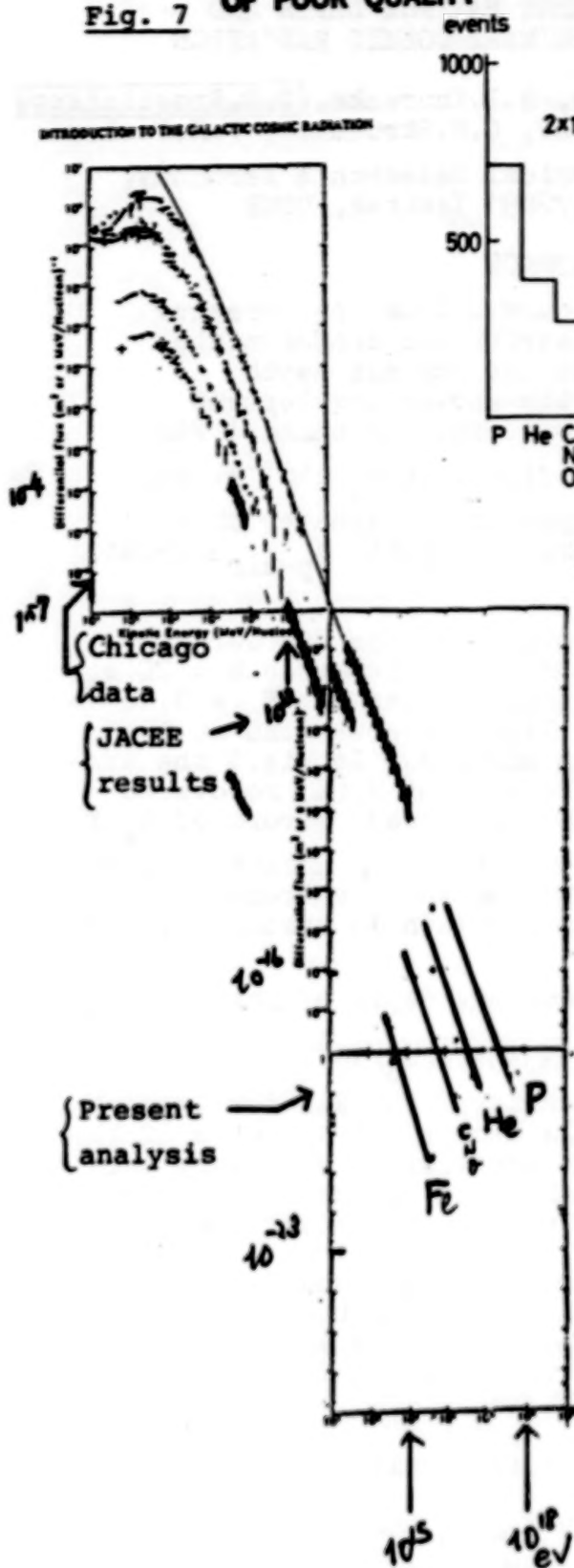
Fig. 6 Primary composition

The number of events which has the same energy (E_0) and the same size has been counted from Fig. 4 and 5. The distribution is given in Fig. 6.

5.Conclusion

It is interesting to plot present result on the differntial spectrum obtained lower energy experiments(Fig. 7). From Figs. 6 and 7, we conclude the composition of primaries in the range of energy 2 $X10^{16}$ eV and 2 $X10^{17}$ eV, the iron component does not become dominant.

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N85-34054

FLUCTUATIONS OF DEVELOPMENT MAXIMUM DEPTH AND NUCLEAR COMPOSITION OF PRIMARY COSMIC RADIATION

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ABSTRACT

The EAS cascade curves from the Cerenkov
light lateral distribution measurements
are recovered and the maximum depth
fluctuations of the shower development
δX_m both on the Cerenkov and charged EAS
components are defined. At $E_0 \simeq 10^{18}$ eV the
mean content of protons is greater than
85%, and p-air cross section $\sigma_{p-air} \leq 750$ mb.

1. Method. The lateral distributions of the EAS Cerenkov
light Q(R) in the interval of the core distances R = 20 $\div$
1500 m and in a wide range of primary energies $E_0 = 8.10^{16} \div$
$1,5.10^{19}$ eV on the EAS Cerenkov light observations at the
Yakutsk array for 1970-1983 are analyzed. In Fig.1 the ave-
rage cascade curves of the EAS electrons $N_e(X)$ recovered
from Q(R) by the method [1] are presented. Errors of $N_e(X)$
due to the measurement errors of Q(R) , the uncertainty of
the angular distribution function of the electrons in part-
ial showers [2] and aerosol distribution in atmosphere [3]
are shown by dashes.

2. Results. Dependence of the average depth of maximum $\overline{X}_{max}$
on E_0 is as follows:
$$\overline{X}_m = (720 \pm 16) + (73 \pm 14) \cdot \lg(E_0/10^{18}) \qquad (1)$$

It is the main not only for a choice of the EAS development
model (here and further we shall mean by it a choice of the
multiplicity law and the energy spectrum of secondary par-
ticles) but also for the determination of the energy depen-
dence of hadron-air cross section and of nuclear composition
of primaries.

The cascade curves presented in Fig.1 and described by
the gamma distribution allow to obtain the total energy E_{EM}
of the EAS electron-photon component on the energy dissipa-
ted by electrons over the observation level X_0.
$$E_{EM} = \frac{\beta}{t_0} \sqrt{1 + 3.5(x_m/x_0)^6} \cdot \int_0^{X_0} N_e(X)dx , \qquad (2)$$
where β is critical energy and t_0 is a unit of radiation
length in the air.

From analysis of relations E_{EM}/E_0 and $N_e(X_m)/N_e(X_m-300)$
we find out that the Landau hydrodynamic model with the
multiplicity law of secondary particles $n_s \propto E_0^{1/3}$ and with

normal law of their rapidities corresponds the most to the experiment. This model also better agrees with experimental energy-dependent fluctuations in X_m:

$$\sigma X_m = (66\pm 4) - (12\pm 2) \cdot \lg(E_o/10^{18}) \qquad (3)$$

The dependence (3) is obtained by data of 980 shower events on a slope of the lateral distribution function (LDF) of charged particles (black triangles in Fig.2)and by 150 events on the recovery methods $N_e(X)$ on $Q(R)$(open squares). This dependence slightly differs from our earlier results [4] owing to more correct account of measurement errors and increase of the EAS statistics. For the comparison in Fig.2 the expected dependences σX_m on E_o are presented for the models HDM and MPM. The latter one has $n_s \propto \ln E_o$ and almost constant energy spectrum of secondary particles in units of rapidities. Nuclear composition of primaries was taken in the calculation as consisting of protons and nuclei of the group VH(A = 51) in different ratios determined by the mean mass number $\langle A \rangle$. Such mass composition at fixed $\langle A \rangle$ gives the largest values of the depth of maximum and its fluctuations in comparison with any other composition of primaries. Therefore at fixed E_o and the EAS development model the low boundaries of errors of X_m and σX_m give the upper estimation $\langle A \rangle$ and σ_{p-air}. An alternative possibility is monochromatic nuclear composition of primaries which leads to the smallest meanings of X_m and σX_m at fixed $\langle A \rangle$.

3. Discussion. In Fig.2 a different character of the dependence σX_m on E_o for HDM and MPM at the same meaning $d\bar{X}_m/d\lg E_o$ = ER is explained by the fact that both models preliminarily were reduced to the same $\bar{X}_m$ = 720 g.cm^{-2} at $E_{\bar{o}}$ = 10^{18} eV by the variation $\langle A \rangle$. Therefore the composition on MPM with the increase of E_o changes from the enriched heavy nuclei ($\langle A \rangle \simeq 40$) to more mixed one and the fluctuations increase. And on HDM the composition from more mixed ($\langle A \rangle \simeq 6$) becomes a purely proton one and σX_m decreases. The opposite character of the dependence σX_m on E_o according to the MPM model at various meanings of ER is caused by the fact that at $(ER)_{calc.} < (ER)_{exp.}$ one should enrich the nuclear composition by heavy nuclei and otherwise - by protons. And only at absolute equality $(ER)_{calc.} = (ER)_{exp.}$ the composition must not change with energy. Obtained σX_m on (3) is in favour of the increase of the interaction cross section with energy and high values of ER $/d\sigma X_m/d\lg E_o/$ evidence the enrichment of the nuclear composition by protons with the increase of E_o, i.e. $d\langle A \rangle/d\lg E_o < 0$.

In Fig.3 the dependences $\bar{X}_m$ and σ_{X_m} on $\langle A \rangle$ for various meanings of p-air cross sections are presented. Here by selection of the scale the experimental data on $\bar{X}_m$ and σ_{X_m} are combined into the dashed region which allows to localize those meanings σ_{p-air} and $\langle A \rangle$ which satisfy the measurements (choice of meanings of these parameters is shown in the bottom in Fig.3)

Thus, if the Landau hydrodynamical model is realized then according to our measurements the mean content of protons in the primary cosmic rays is greater than 85 % and p-air cross section $\sigma_{p-air} \leq 750$ mb at $E_o = 10^{18}$ eV.
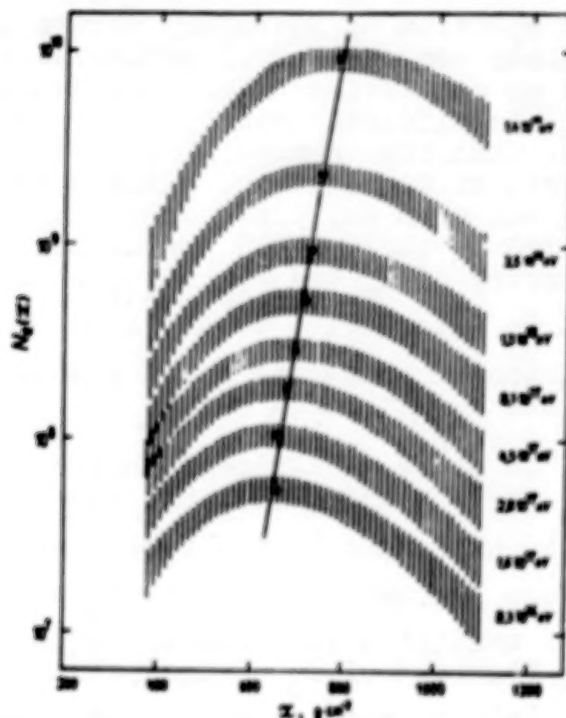
Fig.1. Cascade curves of development of the EAS electrons. Points indicate locations of the maximum depth of the EAS development.
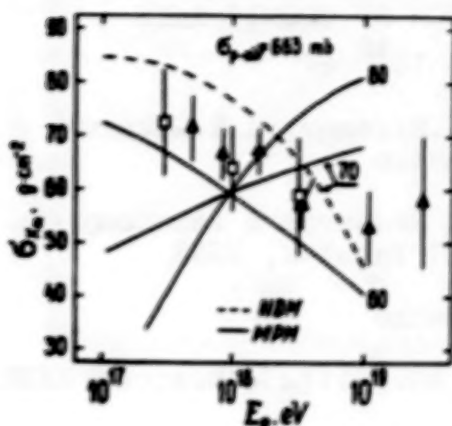
Fig.2.
Dependence of fluctuation value σ_{X_m} of the shower development maximum depth on the primary particle energy. Triangles and squares are experimental data, lines - calculated values. Figures near the curves are $dX_m/d\lg E_0$.
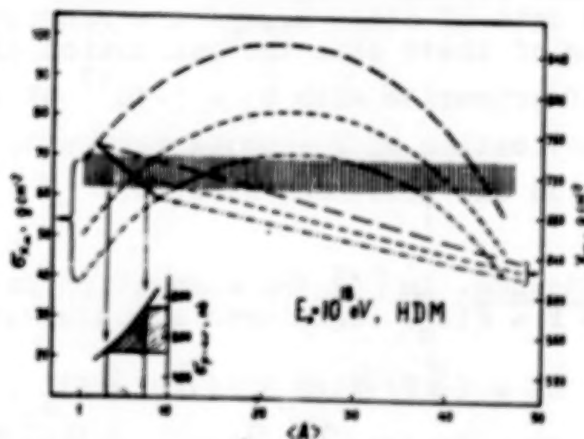
Fig.3. Dependence of the mean value $\bar{X}_m$ and σ_{X_m} on the mean atomic weight of the primary ensemble. Dashed region is the region of measured values $\bar{X}_m$ and σ_{X_m} with errors. Dashed, dotted and dash-dotted lines show the calculation for σ_{p-air} = = 460, 660 and 840 mb, respectively. Values $\langle A \rangle$ and σ_{p-air} which satisfy the experiment are determined by a solid line.

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ESTIMATION OF COMPOSITION OF COSMIC RAYS
WITH $E_o \approx 10^{17} - 10^{18}$ eV

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ABSTRACT

Fluctuations of the shower maximum depth obtained
from analysis of electron and muon fluctuations
and the EAS Cerenkov light on the Yakutsk array
data and data of other arrays are considered. On
the basis of these data the estimation of compo-
sition of primaries with $E_o = 5 \cdot 10^{17}$ eV is re-
ceive. Estimation of γ-quanta flux with $E_o \geqslant 10^{17}$ eV
is given on the poor-muon showers.

1. <u>Introduction</u>. In [1] the elongation rate theorem for
any parameters $P = P(X_m)$ registered at observation level X
was obtained:

$$ER = (\partial P / \partial \lg E_o)_X / (\partial P / \partial X)_{E_o}, \qquad (1)$$

$$ER = (X_m/X)(\partial P / \partial \lg E_o)_X / (\partial P / \partial X)_{E_o} \qquad (2)$$

From here it follows:

$$\sigma(X_m) = (\sigma P)_X / (\partial P / \partial X)_{E_o}, \qquad (3)$$

$$\sigma(X_m) = (X_m/X)(\sigma P)_X / (\partial P / \partial X)_{E_o} \qquad (4)$$

Formulae (1) and (3) are used when $P = P(X - X_m)$, (2) and
(4) - for parameters $P = P(X_m/X)$.

2. Experimental $\sigma(X_m)$ and ER. When estimating ER and
$\sigma(X_m)$ from the lateral distribution function (LDF) of the
EAS Cerenkov light it is necessary to use (1) and (3) [2].
Let's introduce the LDF for R = 200-600 m as $Q \sim R^{-n_Q}$.
According to our data we obtain $(\partial n_Q / \partial \sec \Theta)_{E_o} = 1.9 \pm 0.3$;
$(\partial n_Q / \partial \lg E_o)_X = 0.13 \pm 0.02$ and $\sigma(n_Q)_X = 0.123 \pm 0.018$.
Corresponding to them the meanings ER and $\sigma(X_m)$ are given
in the Table.

Formulae (2) and (4) are used in the case of LDF of charged particles. At the Yakutsk array the LDF approximation as

$$\rho(R) \sim (R/70)^{-1}(1+R/70)^{-b}$$

is accepted: $(\partial b/\partial \lg E_0)_x = 0.16 \pm 0.05$; $(\partial b/\partial \sec\theta)_{E_0} = 1.8 \pm 0.4$; $\sigma(b)_x = 0.2 \pm 0.02$. On data [3] for $E_0 = 5 \cdot 10^{17}$ eV the $X_m = 680$ g/cm^2. Obtained results are given in the Table.

Analogous estimations of ER and $\sigma(X_m)$ follow from analysis of ratios of the EAS Cerenkov light density to electrons $\lg(Q/\rho_e)$ and electrons to

Table

Parameter	ER	$\sigma(X_m)$	Work
n_Q	70±17	66±18	our
b	61±28	78±30	-"-
$\lg(Q/\rho_e)$	64±17	60±20	-"-
$\lg(\rho_e/\rho_\mu)$	70±22	71±30	-"-
$\lg(\rho_\mu/\rho_e)$	79±18	60±16	[4]
$T_{70}(\mu)$	73±23	78±22	[4]
LDF(ρ_c)	79±14	71±6	[5]
$\tau_{1/2}(\rho_c)$	70±5	60±4	[5]
$\tau_{1/2}(Q)$	45±17	60±12	[6]
LDF(Q)	-	69±14	[7]
Average	68±6	68±6	

muons with $E_\mu \geq 1$ GeV $\lg(\rho_e/\rho_\mu)$ measured at R = 300 m from a shower core (Table).

3. Estimations of Composition. To estimate the composition of primaries we use average $\langle ER \rangle$ and $\langle \sigma(X_m) \rangle$ from the Table. In [8] it is shown that based upon superposition principle for any mixed composition $\langle \ln A \rangle = \sum w_i \ln A_i$ and for dispersion $\sigma^2_{\ln A} = \sum w_i (\ln A_i - \langle \ln A \rangle)^2$ we have:

$$\sigma^2(X_m) = \sigma^2_{\langle \ln A \rangle} + (K^2 \sigma^2_P + C^2)\sigma^2_{\ln A}, \qquad (5)$$

where σ_P and $\sigma_{\ln A}$ are fluctuations of X_m at proton or any other pure composition with atomic number $\langle \ln A \rangle$:

$$\sigma_{\langle \ln A \rangle} = \sigma_P(1 - K\langle \ln A \rangle).$$

We accepted K = 0.15, C = 0.43 $\langle ER \rangle$ = 29+4 g/cm^2, $\sigma_P = 56$ and 71 g/cm^2. Calculation results are shown in Fig.1. The region limited by dashed lines corresponds to experimental values $\langle \sigma(X_m) \rangle$ = 68±8 g/cm^2.

It is seen that the experiment contradict the composition of the primaries at $E_0 = 5 \cdot 10^{17}$ eV only from heavy nuclei or the mixed composition with large

Fig.1

content of heavy nuclei.

In Fig.2 experimental fluctuations of muon number $N_\mu(\geqslant 1$ GeV$)$ taken into account of instrumental errors are shown. The calculations on the models [3] for our experiment are shown by lines. The mixed composition of primaries included: 31% - A=1, 22% - A=4, 12% - A=14, 21% A=31 and 14% - A=51 ($\langle\ln A\rangle = 1.88$). The cross section of inelastic processes were used as in [9]. Fluctuations of X_m in showers from primary nuclei were found according to the superposition principle. Experimental meanings of X_m are taken from [3].
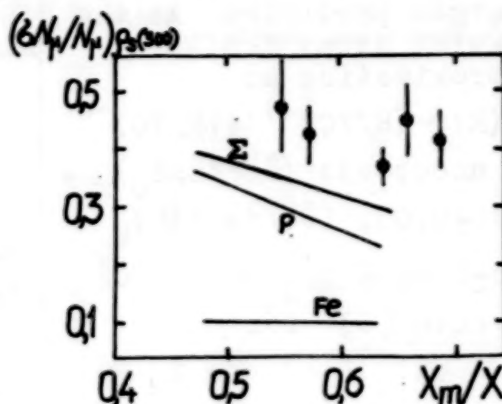
Fig.2.

As before the experiment contradicts the composition only from the heavy nuclei but the expected fluctuations at mixed composition are smaller than the measured ones. Agreement at mixed composition will be if to account cross section growth 1.5 times slower than it is in [9].

4. γ-quanta. In [10] experimental results of the muon component measured at the Yakutsk array by 3 underground scintillation detectors with total area 108 m^2 and with 1 GeV threshold are presented. Each detector consists from 6 sections with the area 6 m^2 each. 1000 showers with $\theta \leqslant 45°$ and effective registration area $3,7 \cdot 10^5$ m^2 for 14000 hours were selected.

The whole massif of the showers for anomalously small content of muons is analyzed. In Fig.3 one event which has the measured muon number 12 times lesser than the expected one ($4,6\sigma$ deviation) is shown. Such a deviation cannot be explained by any fluctuations of the shower maximum depth and by Poisson fluctuations of the detector recordings. Therefore this shower is considered to be formed by a primary γ-quantum. If to estimate a total flux of γ-quanta with $E_0 \geqslant 10^{17}$ eV on one event for all the above registration period then their intensity is $2,9 \cdot 10^{-14}$ m$^{-2} \cdot$s$^{-1} \cdot$sr^{-1}, i.e. $\sim 10^{-3}$ from total flux of the primaries with $E_0 \geqslant 10^{17}$ eV. Its arrival direction is in the plane of the Galaxy with coordinates: $b'' = -8°$ and ~~longitude~~ $l'' = 153°$.

5. Conclusions Experimental data on fluctuations of the shower maximum depth and on muon number $N_\mu(E_\mu \geqslant 1$ GeV$)$ at $E_0 \approx 10^{17} - 10^{18}$ eV contradict to the composition only of heavy nuclei. The most clise to the experiment in this energy

Fig.3.
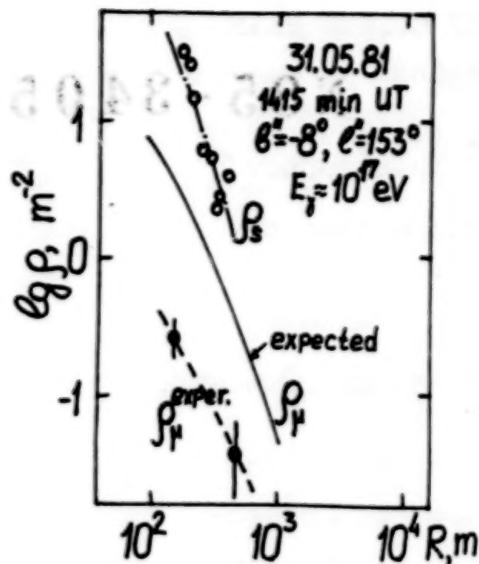
range is the mixed composition which contains not less than 40% of protons ($\langle \ln A \rangle \approx 1,5+0,5$). The only proton composition is though unlikely but it is still impossible to exclude it. The γ-quanta flux is $\sim 10^{-3}$ from the total flux of the primaries at $E_0 \geq 10^{17}$ eV.

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ALL PARTICLE ENERGY SPECTRUM OF COSMIC RAYS
IN 10^{15} to 10^{20} eV Region

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ABSTRACT

Average estimations of the shower energy components are presented and their sum gives $\langle E_o$
$(\rho_{600})\rangle$ - an average function of the relation
of E_o with the shower size parameter ρ_{600} measured at the Yakutsk EAS array. Using this relation to the EAS spectrum obtained at the Akeno and Yakutsk arrays the energy spectrum of the cosmic ray total flux within $15 \leqslant \lg(E_o(eV)) \leqslant 20$
by the EAS methods is recovered.

1. Introduction. Earlier beginning from 1971 we estimated the primary energy E_o on the atmospheric Cerenkov light flux density on the core distance 400 m at the Yakutsk EAS array [1] . Last years the experimental data on a maximum depth, muon energy spectrum and other average characteristics of the EAS development are obtained which are important to estimate the shower energy components. By a balance of the latters one can determine the E_o.

2. Estimation of E_o by Energy Balance Method. The shower primary energy consists of the next components: $E_o = E_{ei} + E_{\mu i} + E_{hi} + E_{e} + E_h + E_\mu + E_\nu = E_i + E$, where the first three terms show the energy loss into the atmosphere ionization (E_i) by electrons, muons and by splitting the nuclei and the last four ones - the energy dissipated in the earth in the form of electron-photon, nuclear-active, muon and neutrino components (E). Our estimation [2] differs from one [4] by accounting of the atmospheric Cerenkov light losses [5]on which E_{ei} - a main component of the E_o is estimated and by use of the new measurement results of the muon energy spectrum for E_μ.

$\underline{E_{ei}}$. For $10^{17} \leqslant E_o \leqslant 10^{19}$eV the relation of E_{ei} with the atmospheric Cerenkov light total flux φ_H(in number of photons) and from the depth of maximum of showers X_{max} (g.cm^{-2}) is given by $E_{ei} = 2.07 \cdot 10^4 (1.04 + 5.8 \cdot 10^{-4} \cdot X_{max})^{-1} \cdot$ $\cdot \mathcal{T}^{-1} \cdot \varphi_H$,eV where $\mathcal{T} = \mathcal{T}_m \cdot \mathcal{T}_a < 1$ is a light transmittance

coefficient by atmosphere due to molecular (Rayleigh J_m) and aerosol (J_a) scatterings. According to [6 et al] a main aerosol part is in a ground layer of ~1 km thickness. If to assume that the aerosol is concentrated at depth > 900 g.cm^{-2} and $J = 0.6$ at $E_o = 10^{16}$eV then $J = 0.62$ at E_o 10^{18}eV. According to these estimations we took $J = 0.60 \pm 0.04$. Then due to the experimental dependence X_{max} from ρ_{600} and the observed correlation of φ_H with ρ_{600} [7] we found the average value $\lg(E_{\mu}(eV)) = (0.98\pm0.05)\cdot\lg\rho_{600} +$ $+ 17.620^{+0.079}_{-0.097}$.

$\underline{E_{\mu i}}$. Its value is small and is observed to be equal to the average meaning expected from calculations by different EAS development models, $E_{\mu i} = (0.12 \pm 0.09)\cdot E_{\mu}$.

$\underline{E_{hi}}$. If to suppose that the average part of hadrons on the atmosphere $P_h(X) = 0.02\pm0.01$ from $N_e(X)$, average energy of the nuclear splitting $\mathcal{E}_{nd} = 0.5$ GeV [8] and adding the usual ionization losses of hadrons we found $E_{hi} = (5.6\pm2.2)\cdot10^{-2}\cdot E_{ei}$. If $P_h(X)$ and $\mathcal{E}_{nd}$ are somewhat overestimated then it is probably quite compensated in estimation of E_{hi} by not accounted here the effect of photonuclear reactions [9].

$\underline{E_{\mu}}$. When the muon component registration threshold $\mathcal{E}_{\mu,thr} = 1$ GeV, as it is at the Yakutsk array, then $E_{\mu} = \bar{\mathcal{E}}_{\mu}\cdot N_{\mu}(>1$ GeV) where the muon component energy $\bar{\mathcal{E}}_{\mu} =$

$$= [N_{\mu}(>1 \text{ GeV})]^{-1}\cdot\int_0^{\mathcal{E}_{\mu},max}\mathcal{E}_{\mu}\cdot dN_{\mu}(>\mathcal{E}_{\mu}) \simeq a\cdot(\nu-1)^{-1}\cdot$$

$\cdot(1 + a^{-1})^{\nu}$ for the energy spectrum of the shower muons in form $N_{\mu}(>\mathcal{E}_{\mu},GeV)\propto(\mathcal{E}_{\mu}+ a)^{-\nu}$ which refers to one muon with $\mathcal{E}_{\mu}'>1$ GeV. Calculations show that when the muons generated only due to decay of pions and kaons then the muon energy spectrum does not almost depend on the EAS development model and the $\mathcal{E}_{\mu}$ very poorly depends on E_o. From unique measurement results of the muon energy spectrum in showers with $N_e = 2.10^5$ at sea level [10] we find that a = = 10 GeV, $\nu = 1.64$ and $\bar{\mathcal{E}}_{\mu} = 18.2$ GeV. At $\mathcal{E}_{\mu,thr} = 1.1$ GeV [11] , 5 GeV [12] and in the case $N_e = 10^6$ [13] the results confirm the mentioned approximation (Fig.1). Using $\bar{\mathcal{E}}_{\mu} = (16 \pm 3)$GeV and the observed relation $\lg N_{\mu}(>1$ GeV)= $= (0.84 \pm 0.08)\cdot\lg\rho_{600} + 6.491^{+0.042}_{-0.046}$ [3] we obtain

$$lg(E_{\mu}, [eV]) = (0.84 \pm 0.08) \cdot lg \rho_{600} + 16.699^{+0.086}_{-0.107}$$

E_{ν}. Assuming that the neutrino carries away 27, 90 and 67% of the muon energy due to decay of pions, kaons and muons, respectively, and the ratio of kaons to pions is 0.22 ± 0.09 [8] we obtain $E_{\nu} = (0.64 \pm 0.18) \cdot E_{\mu}$.

Adding all the above components of E_0 based considerably on the experiment the average estimation is as follows:

$$lg(E_0, [eV]) = (0.98 \pm 0.03) \cdot lg \rho_{600} + 17.754^{+0.066}_{-0.077}.$$

3. Energy Spectrum of the Primaries. Using the above estimation of E_0 for the EAS spectrum obtained on the Akeno and Yakutsk array data in a corrected form [3] the energy spectrum of all the particles at energies $15 \lesssim lg(E_0, [eV]) \lesssim 20$ is recovered. It is shown in Fig.2 where the dashed lines correspond to the results at $E_0 \pm \Delta E_0$. As it is seen this spectrum reveals significant irregularities and being approximated by a form $J(E_0)dE_0 \propto E_0^{-\gamma -1}dE_0$ it has the following exponents:

ΔlgE_0	15.$\div$16.	16.$\div$17.5	17.5$\div$18.2	18.2$\div$18.9	18.9$\div$19.4	19.4$\div$20.
γ +1	2.59$\pm$.18	2.91$\pm$.13	2.99$\pm$.04	3.63$\pm$.05	2.47$\pm$.09	3.48$\pm$.11

Integral intensities with account of accuracy of the determination of E_0 are as follows:

$lg(E_0, [eV])$	15	16	17	19
$I(>E_0)$,m.s.sr	$(2.3 \pm 0.6)10^{-6}$	$(5 \pm 1.6)10^{-8}$	$(6 \pm 2)10^{-12}$	$(3 \pm 1)10^{-14}$
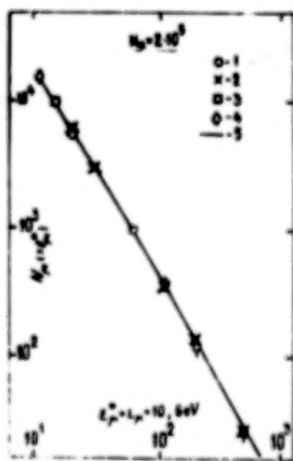
Fig.1.   1- [10], 2- [13],
3- [12], 4- [11],
5- $N_{\mu}(>E_{\mu}) \propto (E_{\mu} + 10)^{-1.64}$
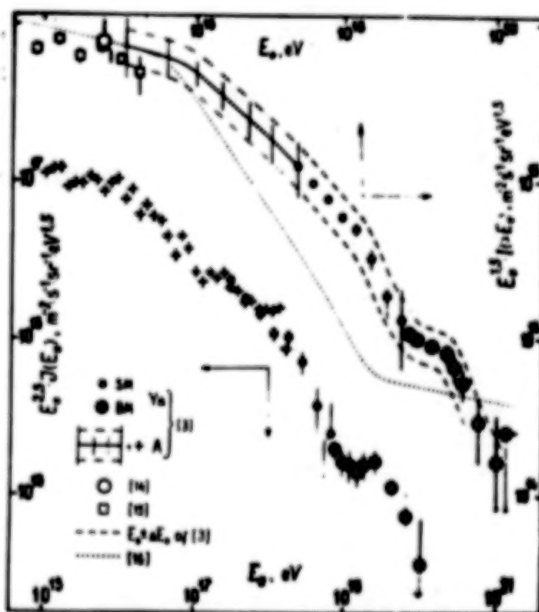
Fig.2.   1-Yakutsk and 2 - Akeno [3], 3- [14], 4 - [15], 5- at $E_0 + \Delta E_0$ (upper) and $E_0 - \Delta E_0$ (lower), 6 - [16].

<u>4. Discussion</u>. A good agreement with results of energy balance of small EAS [14] and of a direct calorimetry [15] testifies a correctness of $E_o - \rho_{600}$ obtained by us. The latter one is $lgE_o = (0.94 \pm 0.03)(lgN_e - 8.042) + 17.754^{+0.066}_{-0.077}$ for measurements at Akeno (920 g.cm^{-2}).

For $lg(E_o, [eV]) \lesssim 19$ the spectrum reveals a consistent steepening with energy E_o which considerably differs from its earlier accepted form [16 et al]. It more corresponds to a picture expected at the diffusion of the mixture of the galactic origin nuclei [17]. The irregularity (rather "bump"-type) at $19 \lesssim lg(E_o, [eV]) \lesssim 20$ is difficult to interpret by evidence of an extragalactic component: the particles of these energies also arrive from low galactic latitudes mainly and their anisotropy phase changes with E_o [18 et al].

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EAS SPECTRUM IN THE PRIMARY ENERGY REGION ABOVE 10^{15} eV BY THE AKENO AND THE YAKUTSK ARRAY DATA

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ABSTRACT

The EAS spectrum on scintillation density ρ_{600} in primary energy region $E_0 \simeq 10^{15} - 10^{20}$ eV on the Yakutsk array data and recent results of the Akeno is given.

1. Introduction

At present the EAS observations at sea-level take the widest energy range of primaries. The observed EAS spectra on particle number N in a shower at $E \leq 10^{18}$ eV and on particle density ρ_{600} at a distance R=600 m from axis at $E_0 > 3.10^{17}$ eV are obtained. Either for the recovery of the spectrum on E_0 or for the comparison it is reasonable to obtain these results in a form of "corrected" spectra where effects of the development fluctuations (different for N and ρ_{600})

and N and ρ_{600} measurement dispersions (different for various arrays) are taken into account. To consider the EAS spectrum on the whole it is required also to use in the analysis a common basic unit of measurement of the shower particle number (density) and a common parameter of the shower size. Yet it is reasonable and possible only on the basis of ρ_{600} : there is the experimental estimation of ρ_{600}

and E_0 relationship and only in the Akeno array data there is the possibility of transition from N to ρ_{600} .

2. Results

a) Yakutsk. In the central part of the array [4] the registration of showers was triggered by a small master (SM) and on the whole array - by a big master (BM). For the analysis the shower events were selected with an axis within fixed receiving areas (different for various ranges of ρ_{600}) and for those periods of the array operation T, when ~100 % - efficiency of registration and levels of $\delta\rho_{600}$ summary relative deviations of fluctuations of the shower development and their measurement dispersions obtained from a total measurement simulation [5] and accepted for the analysis [1,2] were provided. Each shower was individually treated as follows: 1) from approximation of measured particle densities

by $\rho(R)_i \propto R^{-n_i}$ [5] n_i and $\rho_{600,i}$ were determined; 2) $\rho_{600,i}$ was reduced to the zenith angle $\theta = 0^\circ$, atmospheric temperature 240 K and pressure 1005 mb (ρ_{600} and E_0 relationship at the atmospheric depth $X=1025$ g.cm^{-2} at these parameters was found) using the absorption length measured in the experiment $\lambda(\rho_{600}) = (218 \pm 15) + (172 \pm 15) \cdot \sec\theta$, g.cm^{-2}, $\theta < 60^\circ$, a barometric coefficient $\alpha_p = -0,25 \pm 0.03$ % per mb and temperature coefficient $\alpha_T(\rho_{600}) = 0.30 \pm 0.11$ % per K. For $-0.35 < \lg\rho_{600} < 0.6$ as an intermediate parameter of shower size the $\rho_{300,i}$ having the absorption length $\lambda(\rho_{300}) = 251 \pm 21$ g.cm^{-2}, $\theta < 40^\circ$ and $\rho_{600} = (0.14 \pm 0.01) \cdot \rho_{300}^{0.89\pm0.02}$ were used.

Data used in spectrum construction on the whole have following common characteristics:

	$\lg[\rho_{600}, m^{-2}]$	$\delta\rho_{600}$	$ST\Omega$, $m^2 \cdot s \cdot sr$	Number of events
SM	$-0.35 \div 1$	$0.40 \div 0.17$	$(0.16 \div 4.33) \cdot 10^{13}$	534
BM	$1 \div 1.5$	$0.22 \div 0.21$	$(1.88 \div 4.40) \cdot 10^{15}$	109
BM	> 1.5	0.21	$5.69 \cdot 10^{15}$	79

Introducing into the observed intensities the corrections for the summary effect of the development fluctuations and measurement dispersions with the correction factor [2] $K = 0.98 [1 + \delta\rho_{600}^2]^{-0.5\varkappa(\varkappa-1)}$ the differential $f_0(\rho_{600})$ and the integral $F_0(>\rho_{600})$ corrected EAS spectra (see Figure) were obtained.

The differential spectrum for $-0.3 < \lg\rho_{600} < 1.7$ displays significant irregularities and at the description by $f_0(\rho_{600}) = A(\rho_{600}/10)^{-\varkappa-1}$ has the following parameters:

$\lg\rho_{600}$	$-0.3 \div 0.5$	$0.5 \div 1.2$	$1.2 \div 1.7$	$1.7 \div 2.3$
$\lg A$	$-13.37 \div 0.04$	$-13.63 \div 0.02$	$-13.92 \div 0.05$	$-13.20 \div 0.09$
$\varkappa + 1$	$2.95 \div 0.04$	$3.58 \div 0.05$	$2.45 \div 0.10$	$3.43 \div 0.11$

The spectrum on ρ_{600} obtained by the relationship $\rho_{600} = (2.05 \pm 0.11) \cdot (Q_{400}/10^7)^{0.99\div0.02}$ from the transformation of the density spectrum of the shower atmospheric Cerenkov light Q_{400} [1] and having the form of the spectrum of loss in atmosphere confirms the change for $-0.3 < \lg\rho_{600} < 1$.

In the Figure a dashed line corresponds to the observed spectrum on Haverah Park data [6] reduced by us to the scintillation density ρ_{600} due to [7]. In this case according

to [8] the effect of $\delta\rho_{600}$ at $\lg\rho_{600} \leqslant$ 1 is small ($\leqslant 10\%$ on intensities) and at $\lg\rho_{600} \gtrsim$ 1 somewhat increases. Taking into account this fact we find a satisfactory agreement of the results of both arrays. It is remarkable that the Haverah Park spectrum reveals also the steepening tendency for $1.8 \leqslant \lg\rho_{600} \leqslant 2.3$.
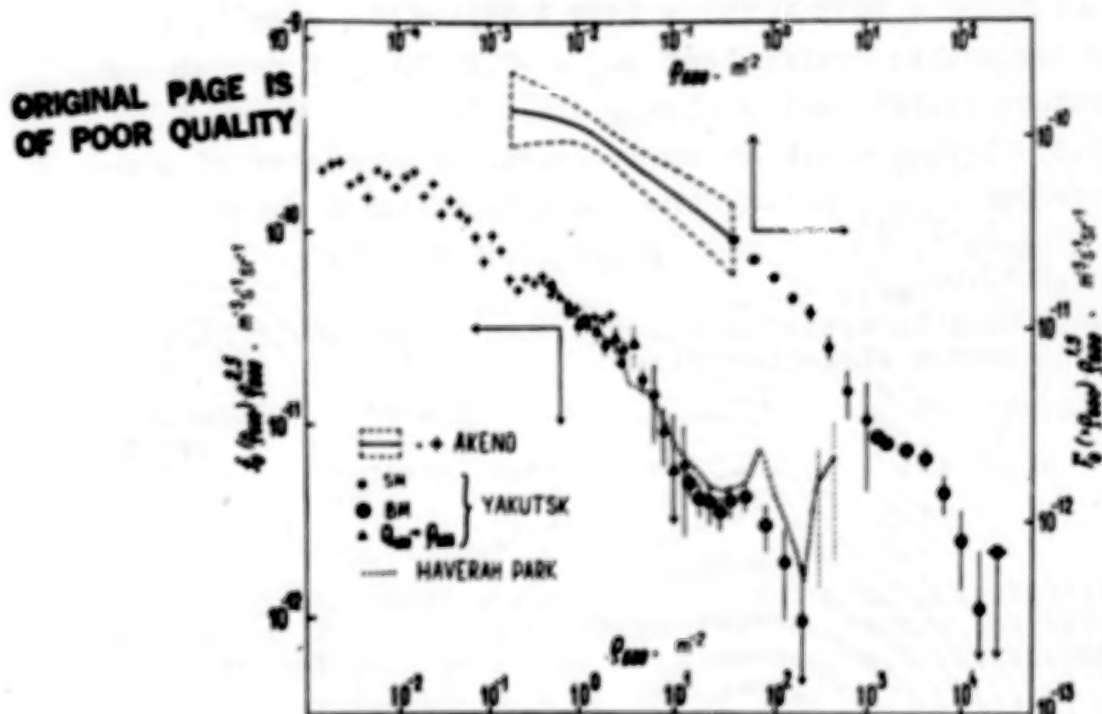
b) Akeno. The observed EAS spectrum at sec θ = 1.1 (at the depth 1011 g.cm^{-2}) is given by $f(N_e)dN_e = A(N_e/10^6)^{-\varpi_N-1}$ with $A = (1.2 \pm 0.2)\cdot10^{-13}$ m^{-2}.s^{-1}.sr^{-1}.part.$^{-1}$, ϖ_N= 1.49 $\pm$0.17 for $5 < \lg N_e < 6$ and ϖ_N = 1.80 $\pm$ 0.12 for $6 < \lg N_e < 8$. Some corrections were made: the spectrum is reduced to the Yakutsk level 1025 g.cm^{-2} with absorption length $\lambda(N_e)$ = 235 g.cm^{-2}; the effect of the shower development fluctuations was taken into account on [9] with average correction factor $\overline{K}_\delta = 0.89\cdot[1 + \delta N_e^2]^{-0.5\varpi_N(\varpi_N-1)}$ = 0.77 where the deviations were taken according to [10] to be 0.7 for $5 < \lg N_e < 6$ and 0.44 for $6 < \lg N_e < 8$.

From [11,12] we find $\lg\rho_{600}^* = \lg[\rho_{600,e}^* + \rho_{600,\mu}^*]$ = = 0.961 $\lg N_e$- 7.46 at the depth 966 g.cm^{-2} at T = 279 K.

Recounting ρ_{600} to depth 1025 g.cm^{-2} with $\lambda(\rho_{600}) = 390$ g.cm^{-2} at $T = 240$ K with $\alpha_T = 0.3$ % per K and to the Yakutsk basic unit of muon equivalent having the relationship $u_\mu/u_e =$ $= 1.15$ with the electron equivalent unit [3] the relationship lg $\rho_{600} = 0.96 \cdot$ lgN$_e$ $- 7.534$ is obtained.

In the Figure the differential and integral corrected EAS spectra on ρ_{600} from the Akeno data are given. For lg ρ_{600} < 0.12 we obtain: $f_o(\rho_{600})d\rho_{600} = A_o(\rho_{600}/10^{-1.80})^{\mathfrak{x}-1}d\rho_{600}$
with $A_o = (1.2 \pm 0.2) \cdot 10^{-5.297}$ m$^{-2} \cdot$s$^{-1} \cdot$sr^{-1}(part./m^2)$^{-1}$, $\mathfrak{x} = 1.55 \pm 0.18$ for $-2.76 <$ lg $\rho_{600} < -1.80$ and $\mathfrak{x} = 1.88 \pm 0.13$ for lg $\rho_{600} > -1.80$.

3. Conclusion

In the considered 5-decade energy range the EAS spectrum on ρ_{600} reveals significant irregularities. For lgρ_{600}<1.2 the steepening(rather consecutive)of inclination of $f(\rho_{600})$ with increase of ρ_{600} occurs: $-\mathfrak{x}-1 = -2.55\pm0.18$; -2.88 ± 0.12; -2.95 ± 0.04 and -3.58 ± 0.05 for Δ lg $\rho_{600} = -2.76\pm-1.8$; $-1.8\div-0.3$; $-0.3\div0.5$ and $0.5\div1.2$, respectively. At lgρ_{600}>1.2 the irregularity is observed: $-\mathfrak{x}-1 = -2.45\pm0.1$ at $1.2 <$ lg $\rho_{600} < 1.7$ and $-\mathfrak{x}-1 \leqslant -3$ at $1.7 <$ lg $\rho_{600} < 2.3$. We assume that four shower events with lg ρ_{600} >2.3 from the spectrum of [6] if to eliminate the effects of methodical character could indicate the possible existence of the other irregularity in the range out of the control of the Yakutsk array.

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COSMIC RAY SPECTRA MEASUREMENTS AT THE YAKUTSK EAS ARRAY

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1. Introduction. The EAS spectra on ρ_{600} obtained at the Yakutsk array for 38000 operation hours in 1974-1982 are presented. The refined value of the conversion factor from ρ_{600} to E_0 is given and based on it the primary energy spectrum is obtained.

2. Methods. At the Yakutsk EAS array the showers are classified on parameters which are well measured in real showers: in the central part - on ρ_{300} and on the whole array - on ρ_{600} . The shower spectra are constructed first on these parameters, then - a single spectrum on ρ_{600} .

The ρ_{300} and ρ_{600} values are determined on the particle lateral distribution function (LDF) obtained in Yakutsk (for instance,[1]) and on approximation $\rho \sim R^{-n}$ using the experimental points closest to R^* (300 and 600 m) [2]. In [1] and [2] somewhat different methods of selection of showers for a construction of spectra are also used.

3. Results. The differential spectra on ρ_{600} from the Yakutsk EAS array data for 38000 operation hours from January 1974 to April 1982 are given in Fig.1. They are presented the physical and instrumental errors of ρ_{600} uncorrected since the conversion factor will be further used for transformation of ρ_{600} to E_0 uncorrected as well.

From Fig.1 it is seen that the spectra obtained by two somewhat different methods do not contradict each other on the whole. However, at $\rho_{600} \leqslant 10$ m^{-2} the spectrum according to [2] is ~ 1.5 times higher than one in [1].

The spectrum ρ_{600} (HP) (Haverah Park) is presented with the recount to ρ_{600} (Y) (Yakutsk) using the dependence ρ_{600} (Y) = $(1,72\pm0,25)\cdot\rho_{600}$ (HP)$^{1,06\pm0,03}$. Such a dependence is obtained from the comparison of the detector responses at these arrays [1].

From Fig.1 the irregular change of spectra, in particular, "bump" at $\rho_{600} > 20$ is evident. However, there is no a common opinion in estimation of such "bump" confidence. To our point of view it is necessary to find out the possible methodical details before concluding the existence of any irregularities of the spectrum, the more so that in this region the insufficient statistics is available and the EAS characteristics at $E_0 > 10^{19}$ eV are investigated not enough.
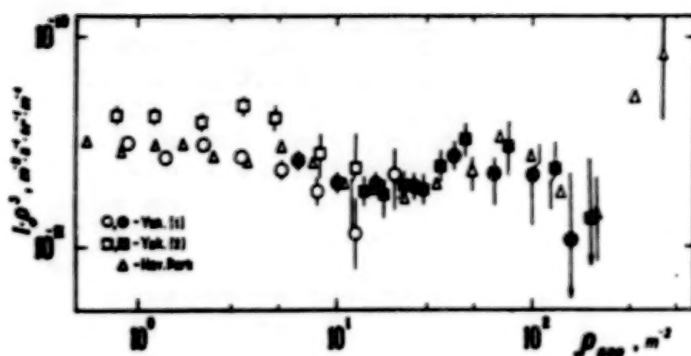
Fig.1

The parameter ρ_{600} for the Yakutsk EAS array is reliably measured and besides it is proportional to E_o. The relationship between ρ_{600} and E_o in [1] is found by the calorimetric method and in [2] - either by the same method or only on the Cerenkov light method (on Q_{400}).

In the total balance of E_o the portion E_1 (energy dissipated by electromagnetic component in the atmosphere) is ~ 80%. It is found as $E_1 = K \cdot \Phi$, where Φ is the total EAS Cerenkov light flux in the atmosphere. The value K depends weekly on the shower development model and is $K \approx$ $3,8 \cdot 10^4$ eV/photon$\cdot$eV^{-1} (photon number is expressed per unit of energy range; for photomultipliers used in Yakutsk the frequency range energy is 2,6 eV).

The conversion factors from ρ_{600} to E_o obtained in [1] and [2] by a calorimetric method differ by 1,4-1,5 times. It is associated mainly with the different estimation of the light absorption in the atmosphere and with the different values of the average energy of muons.

In [1] the light absorption is taken to be $(27 \sec \theta)$%, in [2] it is 40% for all the zenith angles θ. The average energy of muons with $E_\mu \geqslant 1$ GeV is taken to be 7 GeV [1] and it is 16 GeV in [2].

If to suppose that the light absorption occurs only in near the ground atmosphere layer as in [2] and it increases as $\sec \theta$ (i.e. the absorption is $33 \cdot \sec \theta$,%), and if the average energy of muons is taken to be 9 GeV (such a refined estimation seems to be proper), then we obtain:

$$E_o = (5,0 \pm 1,4) \cdot 10^{17} \cdot \rho_{600}(0°)^{0,96 \pm 0,04} .$$

From here we obtain on the Yakutsk EAS array data at sea level the following dependences of charged particle number N_s and of muon number N_μ ($\geqslant 1$ GeV) on E_o:

$$E_o = (7,8 \pm 2,1) \cdot 10^{17} (N_s/10^8)^{0,86 \pm 0,06} ,$$

$$E_o = (1,8 \pm 0,5) \cdot 10^{17} (N_\mu/10^6)^{1,15 \pm 0,04} .$$
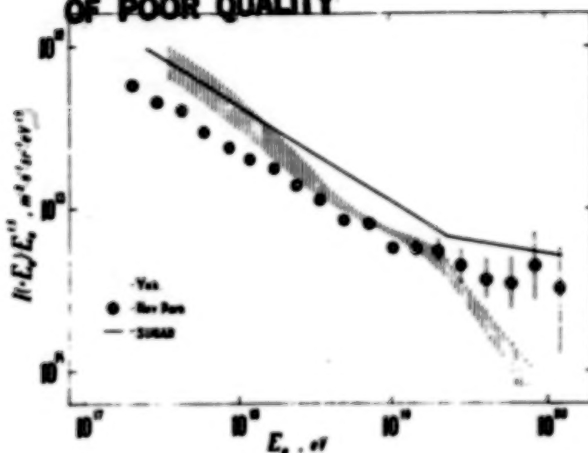
Fig.2

4. Discussion. The integral energy spectrum on the Yakutsk EAS array data by the above conversion factor is presented in Fig.2. The shaded region corresponds to data of [1] and [2]. Note that the achieved at present accuracy of the energy calibration allows to determine the absolute intensity in the range 10^{18} eV with the accuracy to 1,8. The spectrum of the SUGAR array data is presented on [3] using the obtained dependence between N_μ and E_0 and taking into account the difference in thresholds E_μ .

The discrepancy from the Haverah Park spectrum at the extremely high energies is that at the Haverah Park EAS array were registered 4 showers with very high values of ρ_{600} (two last points in Fig.1). At the Yakutsk EAS array such showers were not detected and the experimental data do not contradict the possibility of the existence of cutoff spectrum.

The reasons of the discrepancy of the Yakutsk and Haverah Park ρ_{600} spectra are not completely revealed. It is without exception that there are differences in the geometry of arrays, types of detectors and analysis method.

5. Conclusion. We think that it is necessary to analyze all the details of registration, treatment and analysis of showers based on the common methods to find out the nature of the observed irregularities of spectra.

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COMPOSITION OF PRIMARY COSMIC RAYS NEAR THE BEND FROM A STUDY OF HADRONS IN AIR SHOWERS AT SEA LEVEL

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ABSTRACT

Data on hadrons in air showers arriving at sea level in College Park, Maryland have been studied to find sensitivity to primary cosmic ray composition. The rate of showers which satisfy minimum shower density and hadron energy requirements as well as the rate of showers containing hadrons delayed with respect to the electron shower front are compared to Monte Carlo simulations. The data on the rate of total triggers and delayed hadrons are compared to predicted rates for two models of primary composition. The data are consistent with models which require an increasing heavy nuclei fraction near 10^{15} eV. The spectra which are consistent with the observed rate are also compared to the observed shower size spectrum at sea level and mountain level.

1. Introduction. In this paper we present analysis of a two year run of the Delayed Hadron Experiment at sea level in College Park, Maryland. Four segmented ionization calorimeters (Figure 1), each of area $\sim 1.5 m^2$ were used to study the energy and arrival time distribution of hadrons near the core of
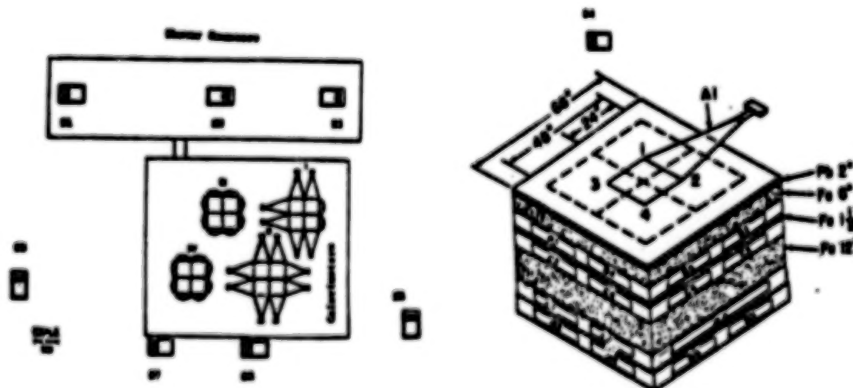
Figure 1: Experimental layout   Calorimeter profile

extensive air showers. A small air shower array of 12 scintillation counters located near the calorimeters were used to record the density and arrival time of the electromagnetic component of the air shower. The details of the design of this experiment have been presented elsewhere.[1]

2. The Experiment. Events were required to pass the following offline cuts in order to be included in our data sample: 1) A signal greater than 75 equivalent particles must be recorded in the top layers of at least one hadron calorimeter. 2) The average shower density in the four counters "A" directly above the calorimeters must have an average density of greater than 13.5 ptls/m^2 and at least two of the four counters must equal or exceed this density. 3) All four A counters must have fired a timing discriminator set at 0.1 particle and shown a timing signal consistent with the other shower counters.

Signals were recorded at four depths in each of four quadrants in all calorimeters. The arrival time of a signal > 3 equivalent particles was recorded for three of these counters within each quadrant. Data from the B layers (located under 150 gm/cm^2) are displayed in Figure 2 as a scatter plot of B
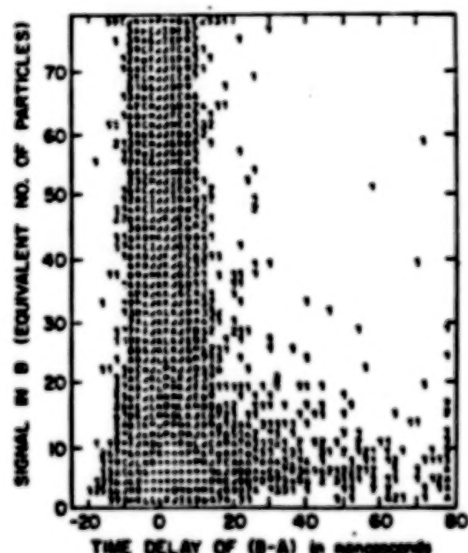
signal against arrival time relative to the A counter above it. Events in which the hadronic counter signal is large are consistent with a resolution of 2.5 ns. The data show several events with large signal and delay (these are described in detail in paper HE 6.2-7 of this conference) as well as a significant tail of low signal delayed events.

The rate of events passing all offline cuts is 3.15 ± .04 events per hour. The rate of events which contain at least one calorimeter counter delayed by greater than 20 ns and having a signal greater than 20 equivalent particles is 0.050 ± 0.004 events per hour. These two event rates are compared to simulations for various compositions in the next section.

Figure 2

3. Simulation of the Experiment. In order to interpret the data taken in this experiment it is necessary to compare it to a Monte Carlo calculation which simulates the interaction of cosmic rays in the atmosphere and the response of our detector to these particles. The details of the air shower simulation used have been given elsewhere.[2] In this paper we shall give a brief description of the simulation.

The program generates air showers in energy intervals from E_0 to $2E_0$ on a spectrum with a slope of $E^{-2.6}$. The data from each of these intervals may then be combined in different proportions to produce different spectra. Over the range of spectral indecies investigated in this work this method produces a smooth spectrum. Nuclei of atomic number A are simulated using a superposition model where A nucleons are generated at the same angle and energy. The simulation uses a cross section which increases with energy for nucleon air interactions.

Interactions are simulated using a modified scaling model in which the rise in central rapidity density seen at the SPS collider is included by steepening the X distribution of produced secondaries in an energy dependent manner. The Monte Carlo includes production of nucleon anti-nucleon pairs as well as pions and kaons. Leading particle effects are included for various projectiles and the effect of nuclear targets is simulated. All hadrons are followed from their production until they either reach detector level, interact, decay or

drop below 2 GeV. The electromagnetic shower is calculated by accumulating each gamma ray produced in a meson decay. The gamma rays are then projected to detector level using approximation B[3] and the lateral spread of their showers is computed using a modified NKG[4] lateral distribution function. The information on both the hadrons and electromagnetic shower are written out on to tape where they are fed into our detector simulation program.

For each hadron which reaches detector level in our simulation we store its energy, position, particle type, momentum, arrival time, and local shower density. The response of our detector to each incident hadron and its accompanying electromagnetic shower is simulated. The number and distribution of triggers and delayed events are computed by applying offline cuts to the simulated data. We then compute an efficiency for triggering for each primary species and energy interval. The simulation of detector response is accomplished by comparison with direct calibration and Monte Carlo calculation.[5]

4. Comparison of Data and Simulation. This experiment provides a set of experimentally measured quantities which may be compared with simulations to test various composition models. It does not measure primary composition directly. Those models which predict rates which are inconsistent with our measured rates can be ruled out within the context of the high energy physics model used. It is important to note that by the use of models which predict significant deviations from observed interaction properties above measured energies different results may be obtained. In this paper, we compare our data to a high energy model which requires a minimum extrapolation from observed data. We also attempt to use models for primary spectra which are consistent with extensive air shower data.

The two models which we consider here represent divergent theories of cosmic ray propagation. In the first (model Md), the spectrum of the light and medium nuclei are assumed to be that given by the JACEE Experiment[6] while the spectra of the heavy nuclei (Si and Fe) are chosen to be somewhat flatter up to a rigidity dependent steeping, resulting in an increasing fraction of heavy nuclei. In the second model (model L), we follow the proposal of Linsley[8] in choosing a proton dominant composition which contains a flattening of the proton spectrum at 10^{14} eV. In Table 1 we list the parameters of each of these models. In Table 2 we present the predicted rates for this experiment for each model.

5. Results. The results of the comparison between our experimental data and our Monte Carlo simulation show that model Md of primary composition which has a significant enrichment of heavy nuclei near the break fits both our trigger rate and delayed event rate. Model L would produce a trigger rate 60 percent above the observed value while producing only 50 percent of the fraction of delayed events observed.

Model Md has been shown to be in agreement with our predicted rates for trigger rate and for delayed event rate. It has also been shown elsewhere to be consistent with measured muon distributions. This model is used to compute the expected flux of air showers at sea level and mountain level. Figure 3 shows these results. The discrepency between the simulation and the reported data[8,9] is consistent with the spread between various measurements.

Table 1
Composition Models

Model Md	Slope (below break)	Break rigidity	Slope (above break)	
Protons	-2.75	200 TV	-3.3	
Alphas	-2.75	200 TV	-3.3	
C-N-O	-2.6	200 TV	-3.2	
Silicon	-2.55	250 TV	-3.1	
Iron	-2.55	200 TV	-3.1	
Model L				
Protons	-2.7	100 TV	-2.5	up to 10,000 TV then -3.1
Alphas	-2.7	800 TV	-3.1	
C-N-O	-2.7	800 TV	-3.1	
Silicon	-2.75	500 TV	-3.1	
Iron	-2.75	800 TV	-3.1	

Table 2
Rate Predictions

Model	Event Rate (per hour)	Delayed Event Rate (per hour)	Fraction Delayed
Data	3.15 ± .04	0.050 ± 0.004	0.018
Md	3.2	0.05	0.015 *
L	3.1	0.04	0.008

* The Md model was chosen to give the best fit to this data.

Sea level   Mountain level
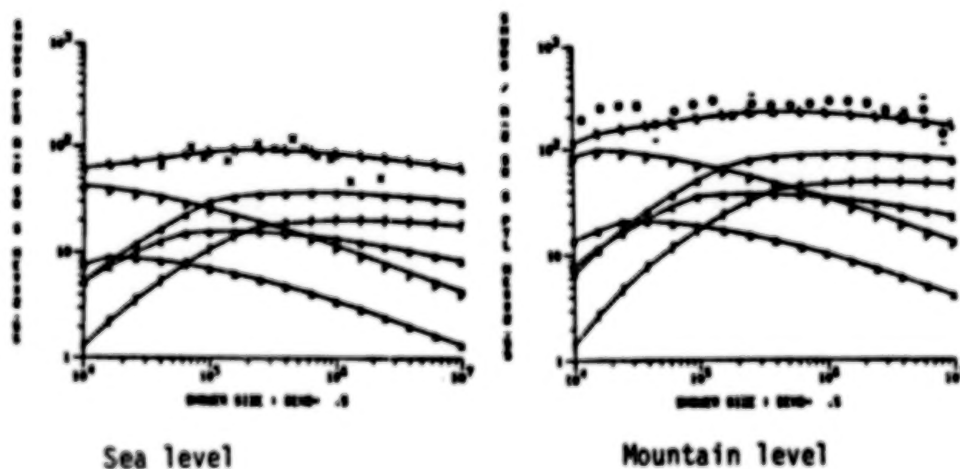
Figure 3: Vertical shower flux: x = sea level data, O = mountain level
data, t = sum of simulated species

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THE COMPOSITION OF COSMIC RAYS NEAR THE 'BEND' (10^{15}eV) FROM A STUDY OF MUONS IN AIR SHOWERS AT SEA LEVEL

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ABSTRACT

A study of the distribution of muons near shower cores has been carried out at sea level at Fermilab using the E594 neutrino detector to sample the muons with $E > 3$ GeV. These data are compared with detailed Monte Carlo simulations to derive conclusions about the composition of cosmic rays near the bend in the all particle spectrum.

We report results from a set of Monte Carlo simulations generating EAS with primary energy in excess of 50 TeV. The set contains showers initiated by protons (A=1), alpha (A=4), CNO (A=14), medium (A=24) and heavy (A=56) primaries. For the primaries heavier than protons a successive breakup model for nucleii-air collisions is assumed. We have, in all, 2300 proton, 1400 alpha, 1000 CNO, 1000 medium and 1200 heavy initiated showers. Each shower record contains details of the electron lateral distribution and the muon and hadron lateral distributions as a function of energy, at the observation level of 1000g/cm.

To simulate experiment, each shower was thrown 500 times randomly over a square of 200 m x 200 m, centered on that of the detector system described elsewhere. For each throw, the electron in the 'trigger' detectors and the muons in the calorimeter were estimated from the lateral distributions. The number of 'detected' electrons and muons in each case was determined by a Poisson fluctuation of the number incident. This set of 'simulated data' was then subject to the same cuts as the data (with an additional upper limit of 100 on the number of muons to take into account the failure of the algorithm that estimates the muons). The resultant predicted distribution of muons, electrons, the rate of events etc. were then compared to those observed. Preliminary results on the rate favors a heavy primary dominated cosmic ray spectrum in energy range 50-1000 TeV.

Composition of Primary Cosmic Rays at Energies $10^{15}\sim10^{16}$ eV Inferred from Mt.Fuji Emulsion Chamber Experiment

Mt.Fuji Emulsion Chamber Collaboration:

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The $\Sigma E\gamma$ spectrum in $10^2\sim 5\times10^3$ TeV observed at Mt.Fuji (~3725 m a.s.l.) strongly suggests that the flux of primary protons in $10^{15}\sim10^{16}$ eV is lower by a factor of $2\sim3$ than a simple extrapolation from lower energies; the integral proton spectrum tends to be steeper than $E^{-1.7}$ around 10^{14} eV and the spectral index becomes ~2.0 around 10^{15} eV. If the total flux of primary particles has no steepening up to $\sim10^{15}$ eV, then the fraction of primary protons to the total flux should be $\sim 20\%$ in contrast to $\sim 45\%$ at lower energies.

1. Introduction. As well known, the integral energy spectrum of all primary particles steepens to $E^{-2.0}$ over $\sim5\times10^{15}$ eV in contrast to $E^{-1.6}$ at lower energies. This "knee" of the spectrum may come from 1) a change of the acceleration mechanism resulting in a steeper source spectrum and/or 2) a breakdown of magnetic trapping in the galaxy. Study on the composition around the "knee" is an important key to resolving the problems of the origin and propagation of cosmic rays. However, the definite result has not yet been obtained because of the too low primary flux for the direct observation and too poor response of the air shower observation to the primary mass.

The emulsion chambers (EC) at Mt.Fuji have been extended to the scale of 1000 $m^2 \times$ year, and a few hundred events produced by primaries with energy $10^{15}\sim10^{16}$ eV have been accumulated[1]. Meanwhile, accelerators has clarified the feature of nuclear interactions up to 150 TeV (in lab. energy). These circumstances enable us to investigate the primary composition around the "knee" by analysing the EC events through simulations based on a reliable model of nuclear interactions.

2. γ-ray Family. A group of high energy particles (mostly γ-rays with energy > a few TeV) produced by successive collisions of a primary particle with air nuclei is called a family. Particles which penetrate deep in the atmosphere can produce families effectively, otherwise

produced particles are usually absorbed in the atmosphere. Therefore protons are most efficient in producing families; the average energy of protons responsible for γ-ray families with $\Sigma E_\gamma > 100$ TeV is $\sim 2 \times 10^{15}$ eV while that of irons is almost one order of magnitude higher.

It has been found that the fraction of proton-induced families in all families in $\Sigma E_\gamma > 100$ TeV is $\sim 70\%$ even if protons constitute only $\sim 10\%$ of all particles around 10^{15} eV. Therefore, if we convert the family intensity into the primary flux assuming that all families are produced by protons, we obtain an upper bound of the proton flux within an accuracy of 30%.

3. Monte-Carlo Simulation. The Monte-Carlo method has been used to simulate the family phenomena and to deduce the primary intensity by comparing the obtained family flux with the experimental one. Important factors in the simulation are the cross-section of nuclear interactions, the leading particle spectrum and the secondary particles spectrum (especially, the degree of scale breaking in the fragmentation region). These are summarized in the following.

Cross Section Using the data of $\bar{p}p$ and pp interactions up to 150 TeV, the mean free path of the N-Air collision is expressed as $\lambda = \lambda_0 \times E^{-\delta}$, where E is in TeV, δ is $0.04 \sim 0.06$ and $\lambda_0 = 82$ g/cm^2.

Elasticity Two cases of the elasticity distribution are assumed as shown in Fig.1. Case A disregards the difference between protons and neutrons and gives the average elasticity of 0.44. In case B is considered the absence of the diffraction peak in charge exchange processes, for which we refer to p-C and p-Be data[3] at 100 – 400 GeV. The average elasticity in a non-charge exchange process like p+Air→p+X is 0.45 while that of p+Air→n+X is 0.28. With a charge exchange probability of 28 %, the average elasticity in case B becomes 0.40.
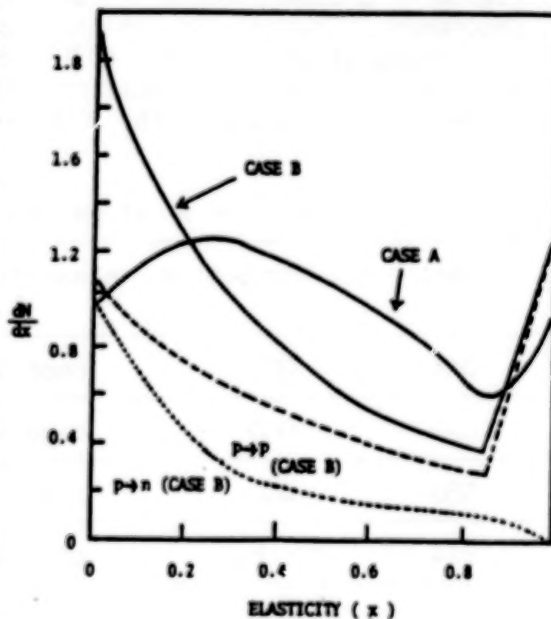
Fig.1 Elasticity distribution.

Energy distribution of secondary particles The QCD-jet[2] automatically introduces a mild scale braking in the fragmentation as shown in Fig.2a. The rapidity distribution shown in Fig.2b is compatible with the CERN-SPS data. To see the effect of a strong violation of scaling in the fragmentation region we employed a fireball model of which the multiplicity grows as $E^{1/4}$.

In Table 1, the models are characterized by the parameters discussed

C - 4

above. The calculated flux of γ-ray families at $\Sigma E\gamma$=100 TeV for each model is listed by normalizing the flux to model QA6.
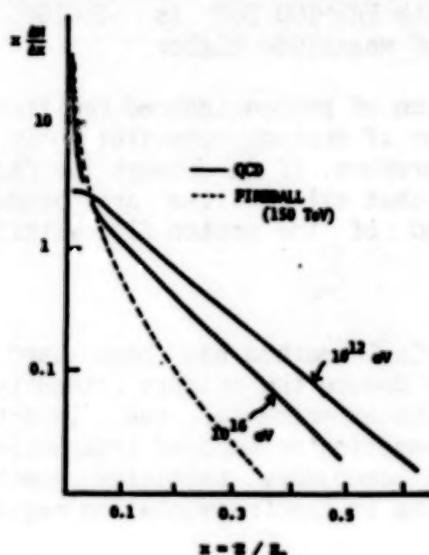
Fig.2a x-distribution of secondary pions in p-Air collisions at 10^{12} eV and 10^{16} eV. A mild-violation of scaling is seen in the model with QCD jet.
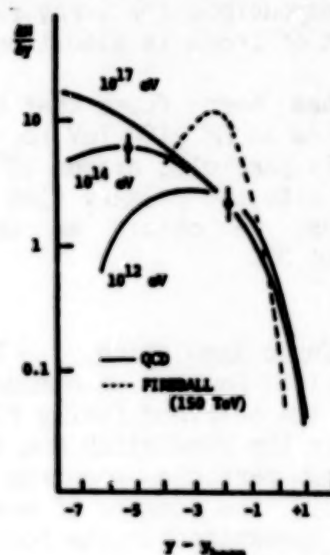
Fig.2b y-distribution corresponding to Fig.1. Black dots show data by the CERN-SPS. Correction due to Air-target effect is included.

Table 1. Interaction model and the relative flux of γ- ray family.

model	x distribution	elasticity	m.f.p.(δ)	flux ratio
QA4	QCD	case A	0.04	1.32
QA6	QCD	case A	0.06	1
QB6	QCD	case B	0.06	0.72
FA4	Fireball	case A	0.04	0.41

4. Proton Spectrum in $10^{15} \sim 10^{16}$ eV. Under the assumption that all γ-ray families are produced by protons, an expected spectrum of protons is deduced as shown in Fig.3. The upper bound is given by model QB6 and the lower one by model QA4. As mentioned already, a maximum of 30 % decrease might take place in the expected flux (due to the heavy primary contribution). Even if we take the experimental errors (both statistical and systematic) into account, we are forced to conclude that the proton spectrum should steepen around 10^{14} eV, and the ratio of protons to all particles in $10^{15} \sim 10^{16}$ eV should be lower by a factor of $2 \sim 3$ than that at lower energies.
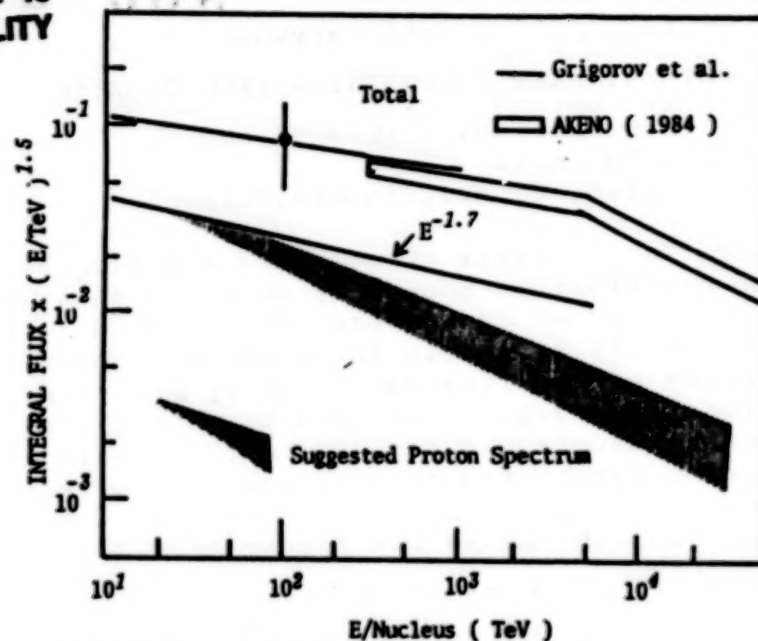
Fig.3 Expected primary proton spectrum.

5. Discussion. By an analysis of air shower data, some authors reported a proton-dominant composition[4]. In their estimation, a scaling violation in the central region are included to be consistent with the CERN-SPS data while the x-distribution in the fragmentation region is not properly considered, which is most effective to the cosmic-ray propagation in the atmosphere. Even if we assume a strong scaling violation (FA4) which is unrealistic already at the accelerator energies as shown in Fig.2b, the expected proton flux never exceeds the simple extrapolation from low energies.

The general (i.e., all observed particles independent of family correlation) hadron and γ spectra observed at Mt.Fuji also supports the present picture[5]. In Ref.6, we estimated the composition around the "knee" by the use of the "rigidity cut-off model". The proton spectrum there is consistent with the present estimation.

Acknowledgement.
Data analysis and simulation calculation were done using the computer FACOM M380 of the Institute for Nuclear Study, the University of Tokyo and the FACOM M180II-AD of Kanagawa University.

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EAS FLUCTUATION APPROACH
TO PRIMARY MASS COMPOSITION INVESTIGATION

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ABSTRACT. The analysis of muon and electron fluc-
tuation distribution shapes by means of the sta-
tistical method of invers problem solution gives
the possibility to obtain the relative contribu-
tion values of the five main primary nuclei groups.
The method is model-independent for a big class of
interaction models and can give good results for
observation levels not too far from the development
maximum and for the selection of showers with fixed
sizes and zenith angles not bigger then 30°.

1.INTRODUCTION. The extensive air showers(EAS)are today
the main and possibly the only information source about the
mass composition of the primary cosmic radiation in the ul-
trahigh energies,because the use of the direct methods are
still limited now to energies 10^{13}-10^{14} eV.

The analysis of the dependences of the second momenta
of the different component fluctuation distributions of the
other EAS parameters/1-4/shous,that the primary cosmic radi-
ation at energies greater than 10^{15}eV can not consist of one
nucley type only and the content of primary protons and iron
nuclei in the mixed mass composition must be essential.

2.METHOD. The EAS fluctuation distribution shapes have
an essential sensitivity/1/to the relative contributions of
the five main nuclei groups:P,α,M,H,VH in the primary compo-
sition of the cosmic radiation with ultrahigh energy,but the
information content could be derived with help of a compli-
cated "noise" system/2,5/.These fluctuation distributions
can be treated as an invers problem/5,6/aiming to precise
the information about the mass composition and to estimate
the relative contributions w_{aj} of the j nuclei groups.

After this point of view/5,6/it is necessary to solve
the invers problem starting from the equation:

$$W_i = \sum_{j=1}^{5} M_{ij} \cdot w_{aj}$$

where M_{ij} is the matrix of the model and apparatus "noises"
for a definite model calculation of EAS development and for
definite EAS experiment(including detector types and arran-
gment,algorithms of the data treatment and so on);W_i are the
the number of showers with a definite $K_\mu = (N_\mu/\langle N_\mu\rangle)$ and $N_e =$const
including the information in the ith-been of the correspon-
ding $W(K_\mu)=W(N_\mu/\langle N_\mu\rangle)$ experimental distribution also; w_{aj} are
the relative contributions of the usual five $(j = 1-5)$ main
primary nuclei groups with $A = 1,4,14,26,52$ in the primary
energy interval $E,E+dE$.

    3. RESULTS AND DISCUSSIONS. Applying the statistical
method of the invers problem solution,developed by V.Pavlju-
chenko/7/by the analysis of pseudoexperimental fluctuation
distributions $W(K_\mu)$ it is shown/6/,that the estimations w_{aj}
are model-independent in the ranges of the errors $\sigma_{w_{aj}}$ if the
conditions $|\alpha_{ex}-\alpha_{cal}| < 0.05$ and $(\sigma_\mu/N_\mu)_p < 0.5$ are satisfied.
This is fulfiled for a big number of interaction models which
describe eventhough the main phenomenological EAS characteris
tics,particulary the muon-size dependence $N_\mu \sim N_e^\alpha$,where α_{cal}
is in the calculated relation $N_\mu \sim N_e^{\alpha_{cal}}$ and α_{ex}-the correspon-
ing experimental value.

    The value $(\sigma_\mu/N_\mu)_p$ depends on the interaction model and
is conected with the shower maximum position over the obser-
vation level in the studed energy range and is a principal
limit for the method of analisis.In this conection an optimal
observation level exists for each energy interval,where the
method of the fluctuation distribution shape analisis gives
the best estimations w_{aj} for the primary mass composition.

    The zenith angle interval,where the showers are regis-
trated,plays an important role in the shower fluctuation in-
vestigations.It is shown/8/,that the muon flux fluctuations
in the interval $\theta < 60^\circ$ are not so informative as in $\theta < 30^\circ$,be-
cause the differences between P and Fe shower fluctuations de-
crease with θ (fig.1).But in the both cases,the relative change
of (σ_μ/N_μ) remains no more than 15%,which is insignificant
for the analysis of the fluctuation distributionshapes.Fur-
ther,the expected differences between muon-size dependences
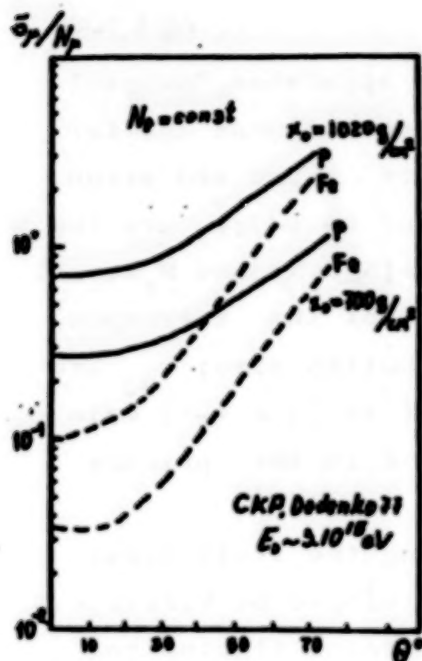
fig.1
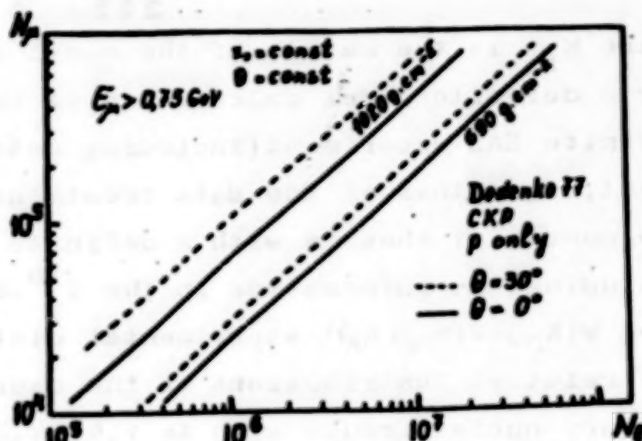
fig.2

for $\theta = 0°$ and $\theta = 30°$ at mountain altitudes are $\sim 10\%$ (fig.2) in distinction to the situation at sea level,where this difference becomes $\sim 50\%$.The corresponding Thien Shan experimental data/9/ confirm this expectation for mountain altitudes(fig.3).From here it follows,that the shower selection of axis in the zenith angel interval $\theta < 30°$ is good enough for the further primary mass composition investigation.
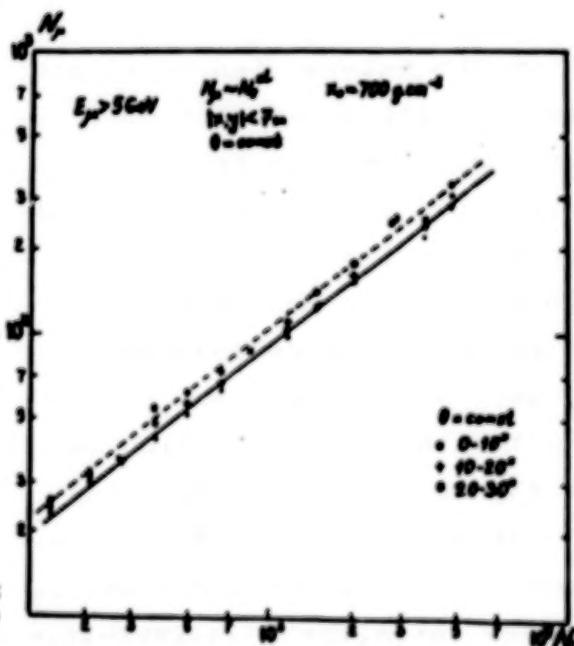
fig.3

The relative primary nuclei group contributions w_{aj} obtained by the solution of the inverse problem are however distored by two factors:

1)the method of the inverse problem solution/6/;

2)the efficiency of the registration of EAS,initiated by primaries with different atomic number A· in the selection of showers with fixed size N_e=const or fixed muon number N_μ= const at the observation level.
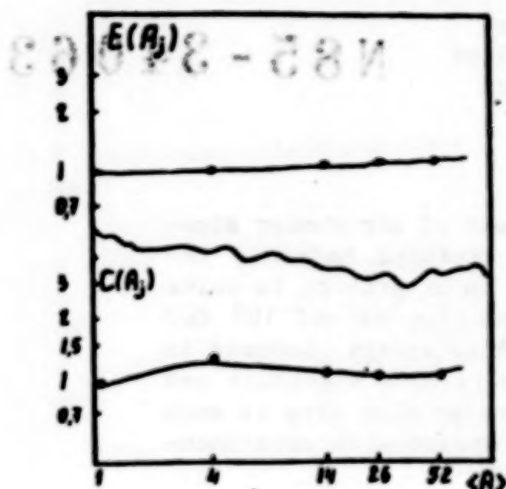
fig.4

These two distortions are dis-
cribed with the corresponding
distortion functions: $C(A_j)$ and
$E(A_j)$ (fig.4).It is shown, that
the biggest systematical correc-
tion is necessary for the w_{aj} va-
lue.The efficiency function $E(A_j)$.
remains very weak for showers at
observation levels not too far
from the development maximum.

4.CONCLUSIONS. Taking into account
all these considerations and re-
marks,we conclude that the primary mass composition in the
energy interval $10^{15} - 10^{16}$ eV,obtained on the basis of the
Tien-Shan data/10/,is mixed and it remains rich on protons
as that at lower energies:

A	1	4	14	26	52
w_{aj} (%)	39 ± 4	13 ± 7	16 ± 6	17 ± 6	15 ± 5

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THE PRIMARY COMPOSITION BEYOND 10^5 GeV AS DEDUCED FROM

HIGH ENERGY HADRONS AND MUONS IN AIR SHOWERS

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ABSTRACT

We present data obtained from a large set of air shower simu-
lation calculations using our highly refined hadronic in-
teraction and shower simulation model, in an attempt to solve
the problem of primary chemical composition beyond 10^5 GeV
total energy. We discuss briefly that high energy hadrons in
air showers offer a rather unique primary mass signature and
show that the interpretation of high energy muon data is much
more ambiguous. Our predictions are compared with experimen-
tal data where such data are available.

1. Introduction. The present work represents a search for observables
and methods that would allow to identify unambiguously the mass group
of a primary initiating a shower from either ground based or deep un-
derground observations. We have shown in our early work (Grieder, 1977)
that the significant information which requires the least number of
simultaneous observables is to be found among the most energetic con-
stituents of air showers. More recently we have shown that high energy
hadrons in air showers observed at ground level offer a unique mass
signature. We have also shown that these data in conjunction with expe-
rimental results indicate that the chemical composition beyond 10^5 GeV
does not seem to change significantly from that at lower energies
(Grieder, 1984).

In the following we summarize the results of our work on the
relationship between high energy muons and primary mass for the energy
range from 10^5 GeV to 10^8 GeV and compare these data with our previous
results based on hadrons.

2. Model and Calculation. The present calculations are based on our
two-component model for hadronic interactions which violates Feynman
scaling in the central region and reproduces CERN pbar-p data very
well. The calculations consider all significant particles and processes
and include the electromagnetic component as well. The essential diffe-
rences between proton and heavy primary initiated showers are due to
the significant difference in the respective inelastic cross sections
and in the high energy nuclear physics that governs the interactions.
Both are considered in our calculations. For the nuclear physics
aspects it is chiefly the fragmentation modi of the primary nuclei and,
above all, the number of collision partners that are involved in nucle-
us – nucleus collisions that are problematic. There our current know-
ledge is still very marginal.

We have shown previously (Grieder, 1983) that it is chiefly this latter problem that troubles the interpretation of high energy muon data with respect to primary composition. In comparison to proton showers, it is the widely varying number of collision partners in the first few collisions of heavy primaries and their subsequent fragments with air nuclei that cause large fluctuations in the secondary particle multiplicity and in a number of other observables, such as the number of high energy muons per shower. In comparison to proton showers, the relative enhancement of muon production in heavy primary initiated showers resulting from the greater height of the first interaction and a lesser energy per nucleon diminishes with increasing primary energy because of the more rapid increase of the cross section for proton primaries in showers of comparable total energy, which rises the point of the first interaction of proton showers, thus stimulating muon production via pion decay. Furthermore, since the energy per nucleon of a proton primary is almost two orders of magnitude higher than that of an iron primary of comparable total energy, the central pion multiplicity is of comparable order of magnitude or larger than the combined multiplicity of fragmentation region pions from all first generation collisions of nucleons from iron nuclei and their fragments.

3. **Results and Conclusions.** In the following we are presenting a set of muon data from our recent all-component calculations. The data are shown in figures 1a) to 1f) and cover a range from 10^5 to 10^8 GeV total primary energy, for proton and iron initiated showers. It was assumed that 10 nucleons of the primary nucleus interact in each of the first iron initiated interactions. Total fragmentation of the nucleus was assumed to occur in the first interaction. Other break-up modi have also been investigated, with the result that distinction between iron and proton showers was even less, as expected.

For low energy muons the well known picture envolves which shows an increase of the muon number with primary energy that goes as energy to power 0.8, with the usual enhancement factor of about 2 or more for iron showers (c. f. figure 1a). However, for muon energies in excess of 100 GeV, relativistic effects in conjunction with the energy and mass dependence of cross sections change the trivial relationship at high primary energy. This becomes evident upon inspection of figures 1b) through 1f). The cross-over of the two curves depends on muon energy, of course, as shown in figures 1d), 1e) and 1f).

Because of the multiplicity law on one hand and the competition between interaction and decay of pions as a function of energy on the other, it is evident that pions from different rapidity regions are responsible for muons of a given energy group resulting from either proton or iron initiated showers of the same total primary energy. These facts in conjunction with the above mentioned high energy nuclear physics aspects govern the muon number in a particular energy group in proton or iron initiated showers.

From the above considerations it is evident that a given muon detector, located at a particular depth underground, corresponding to a

certain energy cut off is only suitable for investigating a distinct primary energy range with respect to chemical composition. Moreover, because of the remaining ambiguities, data from at least two or more underground detectors located at different depths will be required to get a unique answer. Upon folding of the known primary energy spectrum with the multi muon rates, a coarse mass determination can be achieved, provided that the detectors cover an adequate area. Present underground installations are still marginal in size for reliable multi muon detection. This point is discussed elsewhere (Grieder, HE 5.4-4, this conference).
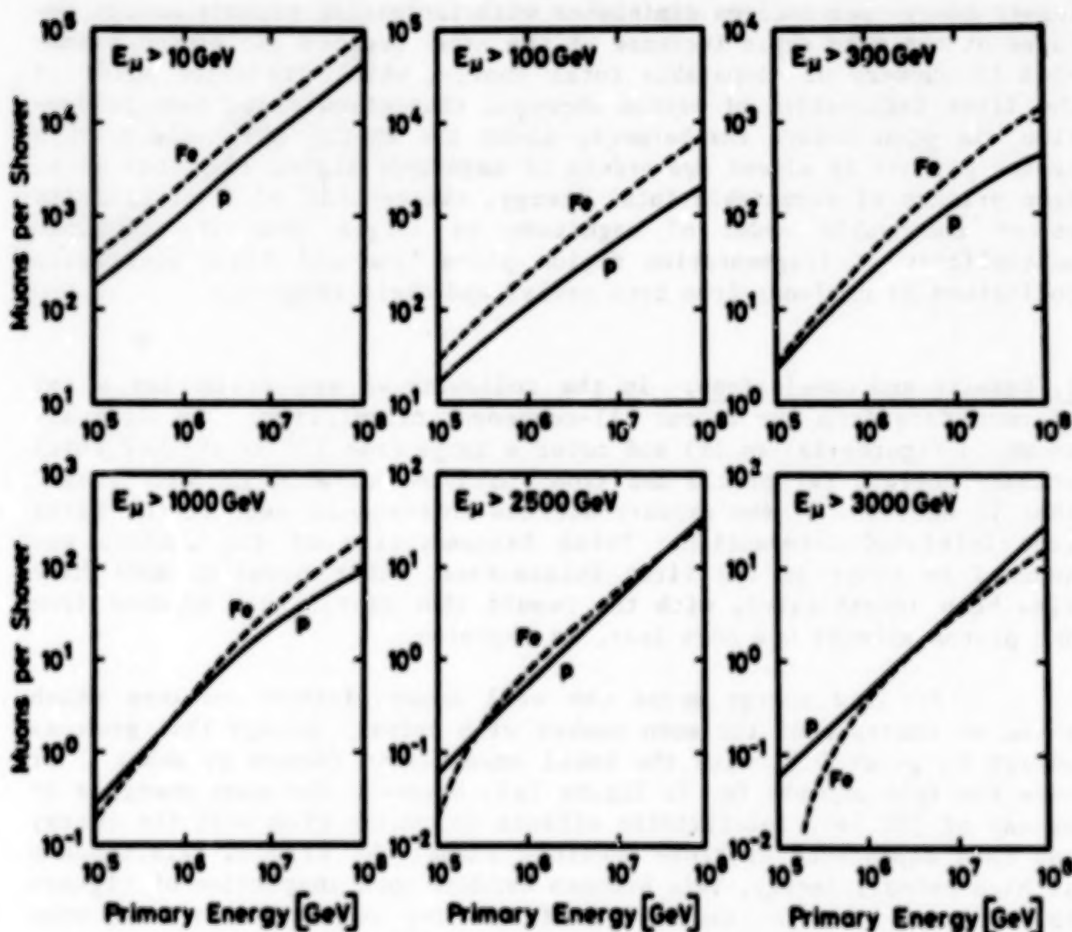
Fig. 1 Muon number versus primary energy in proton and iron initiated showers for different muon cut off energies, as specified.

At lower muon energies experimentally observed correlations between muon number and primary energy (or shower size) have so far failed to manifest an unambiguous transition from a so-called normal to an iron rich composition at the expected location in the primary spectrum, as is shown in figure 2. Thus we also conclude from these data that the composition is more likely to change little if at all, and that the bend in the spectrum is due to another cause.
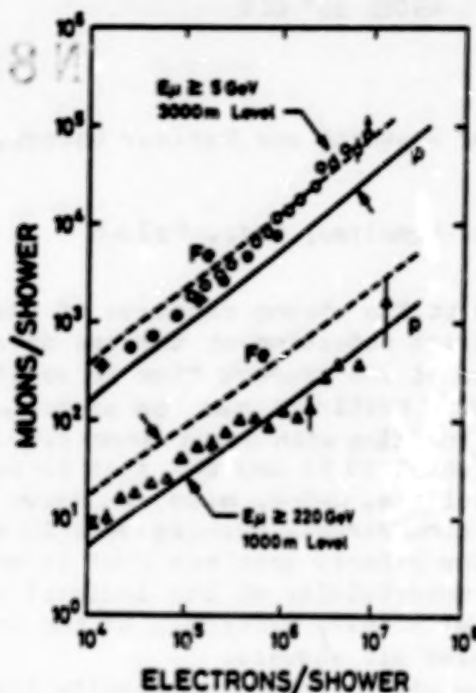
Fig. 2 Muon - electron correlations for proton and iron initiated
showers. The dashed and solid lines are from our calculations.
The full and open circels are experimental data from Tien Shan
(Kabanova et al., 1973 and Machavariani et al., 1979), the
triangular symbols from the Kolar Gold Fields (Acharya et al.,
1983).

Lack of space does not allow us to summarize the hadron data
here. For details on this topic the reader is referred to the earlier
mentioned reference (Grieder, 1984). In spite of the fact that hadrons
offer theoretically a more clearcut primary mass signature than muons,
we fully realize that high energy muons have their experimental merits.

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IMPLICATION OF EAS DATA FOR THE STUDY OF PRIMARY COSMIC RAYS
ABOVE 10⁵ GEV

N85-34064

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1. Introduction Due to the strong decrease of the energetic cos-
mic ray flux its direct detection at the top of atmosphere with
air crafts is limited at the present time to about 10^5Gev. The in-
tensity of all primary particles can be approximated in the range
10^2-10^5Gev by power function with power index 2.65. There are pre-
dominantly protons (about 40 %) and the rest is represented by se-
veral groups of nuclei (He, C-N-O, mean and heavy nuclei). In the
range of 10^5-10^8Gev considerable disagreement is observed between
the estimations of the primary spectrum that is most probably
connected with the uncertainity of the indirect derivation of the
energy and the type of primary particles on the basis of ground
parameters of extensive air showers.
     In this paper we will discuss our results for the primary spec-
trum in the range 10^5-10^8 Gev, obtained by implication of EAS data
from mountain altitudes registered with Tian Shan and Chacaltaya
apparatuses.
2. Energy spectrum of primary cosmic rays at 10^5-10^8 Gev The mean
energy of primary cosmic flux is obtained on the basis of electron
and muon size spectra of EAS. For that purpose we have simulated
the development of electron and muon components in EAS initiated
by primary particles with fixed energy and atomic number. It was
assumed the so called high multiplicity model for hadron interac-
tions, normal mass composition of primary particles that is the same
as below 10^5Gev. From the simulated showers we have constructed the
fluctuation histograms of the total electron number and that of
muons in EAS for several values of primary energy and groups of
nuclei. The histograms are approximated by Gamma distributions the
parameters of which are represented as functions of primary energy.
It allows to obtain the conversion factor , W, with which we can
convert shower size in primary energy, needed in order to obtain
theoretically fluctuation distributions of primary energies. They we-
re used to derive energy spectrum of all primary particles from the
measured intensities of extensive air showers with different elec-
tron and muon size. It is compared in fig.1 with the curve that is
an approximation of the direct registration at lower energies. Our
spectrum derived from the measured electron size distribution of
EAS at mountain altitide smootly links the satelite data showing
some tendency of a bump around 10^6Gev. The spectral index is chan-
ging from 2.4 to 2.76. In the same figure we have compared the
corresponding estimation for primary energy spectrum of Nagano et
al² obtained on the basis of Akeno data. They give too low intensi-
ties of the primaries most probably due to the relatively small
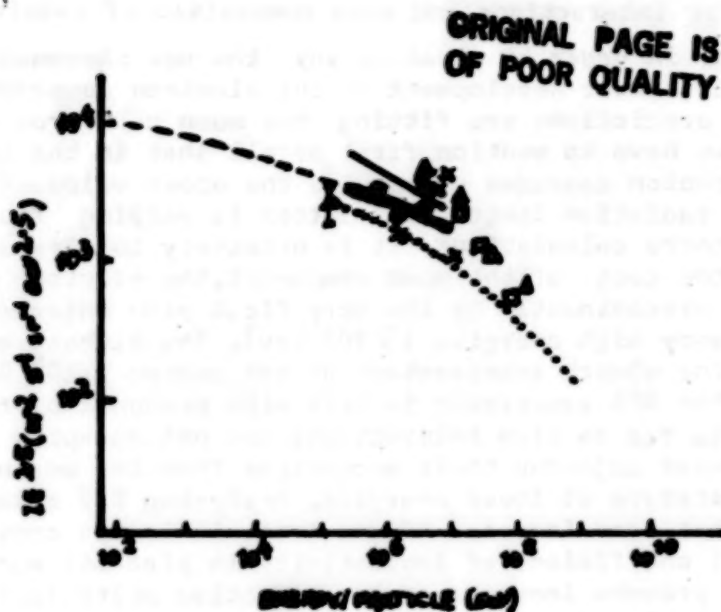
Fig.1 The all-particle energy spectrum ; dash line - approxima-
tion of satellite and baloon data (Grigorov et al[3] o) ;
JACEE collaboration[4] ; thick line - present calculation
on the basis of electron size spectrum; full line - present
calculations for muon size spectrum; dotted line - Nagano
et al[2] estimations on the basis of Akeno data; Khristiansen
et al[5] x ; Efimov et al[6] □ ; La Pointe et al[7] △ .

size of showers detected with fixed intensity. (As a ground para-
meter they used the number of electrons in the maximum of showers.
So far as shower cascade curves are not determined around the ma-
ximum in Akeno (920 $g.cm^{-2}$) these authors have multiplied Akeno
data by the ratio, $N_{max}^{ch}/N_{920}^{ch}$, taken from the Chacaltaya experi-
ments at different zenith angles.

Our primary spectrum derived from the muon size distribution
disagrees with the measured spectrum at lower energies. The high-
multiplicity model predicts higher intensities of all primary par-
ticles from the converting of muon data. They do not link to the
intensities of cosmic particles with lower energies. Better con-
sistency could be obtained if we assume a new phenomenological
model[1] with breaked Feynman scaling, because the latter gives
smaller values for the mean energy of primary particles initiating
showers with a fixed size than in the case of high-multiplicity
model. Apart of that, our complex analysis of all muon data[1] gave
also ground in favour of the new phenomenological model if we
assume normal primary composition in the range 10^5-10^8 Gev. How-
ever, when we applied the new phenomenological model for calcula-

tion of electron component characteristics and for convertion of
electron shower size in primary cosmic ray spectrum we obtain
considerable disagreement. It forced us to inspect both our model
assumptions for interactions and mass compositio of cosmic rays.

3. Discussion In order to clear up why the new phenomenological
model predicts slower development of the electron component of EAS
whereas its predictions are fitting the muon data from different
experiments we have to mention first of all that in the simulation
of electron-photon cascades we assumed the upper value (37.7 g/
cm^{-2}) of the radiation length. The latter is varying from 35 in
different authors calculations. It is necessary to stress also that
unlike with the case of the muon component, the electron component
is governed predominantly by the very first pion interactions[1]
occuring at very high energies ($\gtrsim 10^5$ Gev). The highest accessible
energies of the modern accelerators do not exceed 2.10^5 Gev as is
the case of the SPS experiment in CERN with proton-antiproton colli-
ding beams. So far as pion interactions are not measured at high
energies we have adjusted their properties from the measurements
with accelelerators at lower energies. Analysing EAS data we made
conclusion that some increase of the total inelastic cross section
and the total coefficient of inelasticity in pion-air nucleus colli-
sions should provoke increase of the effective multiplicity and
consequently faster development of the electron component in EAS.
Similar conclusion we derive from the examination of the hadron
component of EAS. In fact there are some experimental evidences[9-13]
low energy accelerator experiments allowing to assume considerably
pion interaction cross section and inelasticity at energies above[14-17]
10^5Gev. However, it must be poined out that several authors
have already shown that such corrections only partly improve the
consistency of the calculated properties of electron and hadron
components of EAS with experimental data.

It is worth-while to note that there is without doubt an in-
crease in the yeld of baryon (and anti-baryon) production at
very high energies observed already in the SPS Collider experiment.[18]
Tonwer[19] finds in cosmic ray experiments strong evidence for such
increase in the fraction of baryons with energy, the value reaching
at least 15 % by 10^5Gev.(The percentage of baryons in our calcula-
tions with high-multiplicity model had been neglected whereas
it was assumed to be about 10 % in the new phenomenological model);
It is certainly possible that the observed fast development of EAS
above 10^5Gev is partly due to the considerable baryon production that
leads to shorter mean path of cosmic ray interactions in the air.

At last we can not dismiss high energy gamma rays in the pri-
mary spectrum above 10^5Gev. All gamma ray sources detected at pre-
sent time have energy spectra wkth power index about 1 in comparing
with 2.6 of other particles. Thus, the γ/proton ratio may appro-
aching 10^{-3} at 10^6Gev [20]. In this connection is the hypothe-
sis of Wdowczyk and Wolfendale[20] that about 30 objects as Cyg X-3 is
needed in the Galaxy to produce the bulk of the cosmic ray particles
if as much energy went into particles as into gamma rays. However
in order to obtain as much muon as they are observed in showers ini-
tiated by gamma rays emitted from the specific sources (Cyg X-3

and Crab) we have to assume some convergence of the electro-
magnetic cross section of photon production to that of the
strong interaction pion production at too low energies (say,
about $10^5 - 10^8$ Gev).

Thus, we can conclude that the problem of determination
of the energy and mass spectrum of primary cosmic flux insists
further complex investigation of both particle interactions at
high energies and the astrophysical mechanisms of different
particles acceleration.

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HIGH-ENERGY MULTIPLE MUONS AND HEAVY PRIMARY COSMIC-RAYS

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Abstract
The three-dimensional simulations have been carried out on high-energy multiple muons. On their lateral spread, the comparison with the deep-underground observations so far indicates that the primary cosmic rays seems to include heavy nuclei of high content. The calculated results also suggest us a method to determine the average mass number of primary particles in the energy around 10^{15} eV.

1. Introduction
The cosmic-ray composition in the energy around 10^{15} eV provides us with a useful clue to clarify acceleration and propagation mechanism of cosmic rays. However, the restriction of observation limits the direct measurements to a lower energy region. On the other hand, on the informations given indirectly from the observations of very high-energy phenomena in the atmosphere, the reliability has increased, because that the characteristic feature of high-energy interactions has been clarified by the scale-up of accelerators.

According to a systematic study of gamma-ray family phenomena observed with emulsion chambers at Mt. Fuji[1],[2], which gives us one of those indirect informations, the heavy-nuclei content seems to increase in those energy region. This feature is consistent with some observations of extensive air showers[3]. In order to investigate further this feature, as described in the previous report[4], we carried out the Monte Carlo simulations on high-energy multiple muons, and compared with the experimental results of deep-underground observations [5],[6]. On the lateral spread of multiple muons, which is not much affected by experimental bias, the observations coincide with those calculated under the assumption of the primary cosmic rays with heavy nuclei of high content. For the purpose of the further examination, our simulation study has been continued with the same method. The results suggest us one of a method to determine the average value of mass number of cosmic rays at very high energy.

2. Simulations
The three-dimensional Monte Carlo simulations have been carried out on the high-energy multiple muons which are produced in the upper layer of the atmosphere and reach to the sea level and also to the point of great depth underground[4].

On the nature of hadron interactions in the atmosphere. It is assumed in the simulations that the Feynman scaling is held in the fragmentation region of particle production and the collision cross section increases as increasing of energy corresponding to the $\ln^2 s$ dependence. In the nucleus-nucleus collision. some of nucleons in the incident nucleus interact with the target nucleons and induce multiple productions of pions and kaons. The remaining part of the incident nucleus breaks up into lighter nuclei and nucleons according to an assumed fragmentation probability. In the above assumptions. we adopt almost the same model parameters as those used in the simulations(5).(6) by which the observed feature of gamma-ray families at Mt. Fuji was investigated. The decay probability of charged pions and kaons into muons depends on the atmospheric density. The structure of the atmosphere is determined on the basis of the US standard atmosphere. Also. the effects are taken into account of energy losses and of geomagnetic field.

3. Results and discussions

The lateral distribution of muons in the simulated phenomena was compared with the experimental results of multiple muons obtained at the great depth underground(7).(8) in the previous report(4). The comparison is shown again in Fig. 1. The parameter of lateral spread r_0 has been determined by assuming muon density $\rho(r)$ expressed as the linear exponential form $\exp(-r/r_0)$. As increasing of mass number of primary particles. the average height of muon production increases. and then the lateral spread of multiple muons broadens. The experimental results on the lateral spread prefer the hypothesis of the primary cosmic rays including heavy nuclei of high content to the proton-dominant case. This feature agrees with the information obtained from the emulsion-chamber experiment(1).(2). By using the above comparison. one may determine the average mass number of primary particles. The lateral spread. however. depends on cross section and transverse momentum of interactions. The obtained value of mass number only by the above comparison is. therefore. influenced by
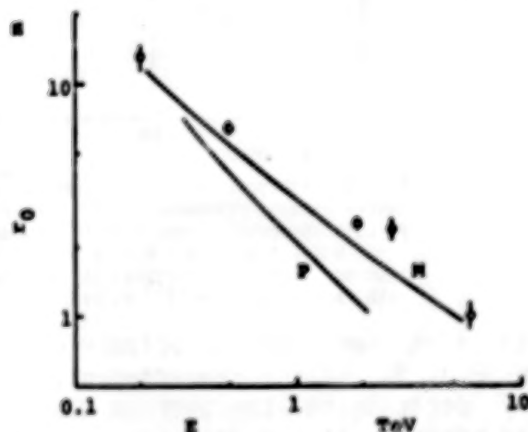
Fig. 1. Energy dependence of the parameter of lateral spread for constituent muons in the multiple-muon phenomena(4). The solid curves represent the simulation results for various values of the threshold energy of muons at sea level E. Two cases are shown of primary cosmic rays: the proton-dominant (P) and the heavy-nucleus-dominant (H) cases. The circles indicate the experimental results at the Kolar Gold Fields(7) (the open circles) and at the Homestake Gold Mine(8) (the solid circles).

their dependence on energy. and includes ambiguity in the assumptions of the calculations.

The figure of energy spectrum of constituent muons in a phenomenon also depends on the mass number of primary particles. The characteristic feature differs with distance from the center of the phenomenon. The spectrum in the case initiated by a heavy nucleus relatively steepens compared to that of a light-nucleus case. In the restricted region within a certain radius near the center. this tendency is much evident. To the contrary, in the region far from the center. the opposite tendency appears. In the intermediate region. the spectral figure does not depend of
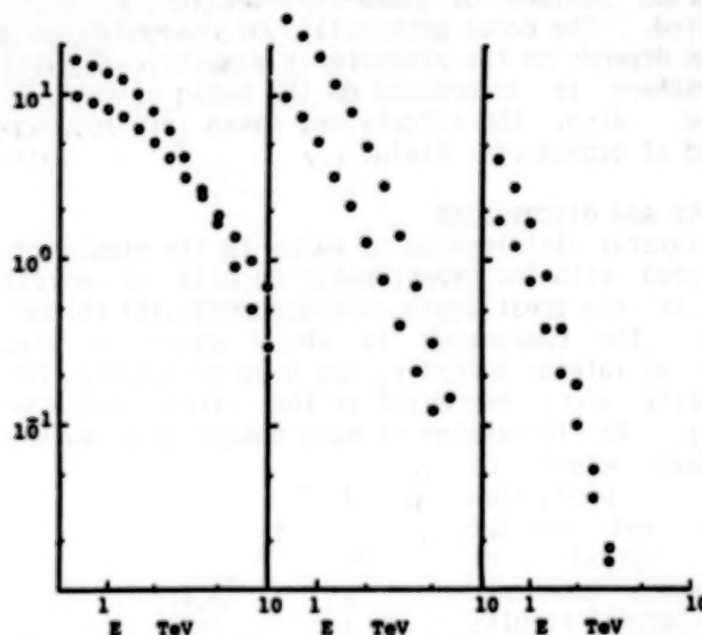
Fig. 2. Integral energy spectra of constituent muons in the multiple-muon phenomena. The circles indicate the simulation results observed at sea level in various ranges. r < 2 m (a). 2 m < r < 6 m (b) and 6 m < r < 10 m (c). for the cases initiated by protons (the open circles) and iron nuclei (the solid circles) with the energy from 10^{15} eV to 10^{16} eV.

the mass number of the primary particle. This feature is shown in Fig. 2. These characteristics allows us to devise a method for determining the average mass number of primary particles. Foe example. if one detects high-energy multiple muons associated with extensive air showers. and measures the energy of their constituent muons in the high-energy region. then he may take the spectra of those muons in various ranges as shown in Fig. 2. The reliability of the calculation and the applied assumptions would be confirmed by examining an agreement between observed and calculated values in the intermediate region where the spectral form does not depend of the mass number of primary particles. The distance of that region shifts according to the assumptions for cross-section value and average transverse momentum. and also the spectral form in that region varies according to the

production spectrum in the fragmentation region of hadron interaction. If the assumptions were not appropriate. the observed results would not coincide with the calculated ones. After the above examination in the intermediate region. a comparison is made of the observed spectral form with the ones calculated for various nuclei of primary particles in the central region. Evaluating the possibility. for example. in the observation of about 3 years using a TeV-region spectrometer of about 20 m^2 in scale observing muons with an air-shower array. the average mass number of primary particles can be determined with an accuracy of about 50 % in the energy around 10^{15} eV. Considering the current situation that the direct observation is not much easy. this is one of the methods to be investigated for the measurements of composition of primary particles. We also anticipate the results on high-energy multiple muons obtained from the huge detecters of proton-decay experiments at deep underground. to be compared with our calculated results.

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COMPOSITION OF PRIMARY COSMIC RAYS NEAR THE KNEE

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Abstract

The size dependence of high energy muons and the size spectrum obtained in the KGF air shower experiment suggest that the mean mass of cosmic rays remains nearly constant at ~ 15 upto 5×10^6 GeV and becomes one beyond. The composition model in which nuclei are removed at 7.5×10^4 GeV/nucleon due to photodisintegration and the proton spectrum steepens at 6.7×10^6 GeV due to leakage from the galaxy, which explains the KGF data, is shown to be consistent with data from other experiments also.

Introduction

Data on various components on EAS from different experiments seem to suggest models of primary cosmic ray composition which are completely at variance with each other. The dependence of number of high energy muons on shower size together with the size spectrum from the KGF experiment[1] suggests that the mean mass number remains nearly constant upto about 4×10^6 GeV and becomes 1 beyond. The size dependence of 5 GeV muons and their fluctuations from the Tien Shan experiment[2] indicate that the composition remains unaltered over a wide range of primary energies which covers the knee in the primary spectrum. The elongation rate derived from early Cerenkov measurements [3,4] and observations on the fraction of delayed hadrons[5] have been interpreted in terms of an iron-rich composition near the knee, resulting from rigidity cut-off with a critical rigidity $\sim 10^5$ GV. Here we show that a composition model in which nuclei are removed due to photodisintegration near the source itself and the proton spectrum steepens due to leakage from the galaxy at a much higher energy, which explains the KGF data, can also account for most of the other data, if proper account is taken of the systematic effects in various experiments.

Composition from the KGF data

The N_μ-N_e dependence of muons of energy $\geqslant 220$ GeV and the size spectrum from the KGF experiment[1] are shown in Fig.1. Acharya et al[1] have shown that the muon data does not agree with the rigidity cut-off model[6] with a critical rigidity of 10^5 GV and extragalactic protons becoming dominant at 10^9 GeV, which predicts an increasing mean mass number with shower size in the size region 10^4-4.10^5 and a high mean mass number at higher sizes. An important feature to be noted from Fig.1 is that the discontinuity in the N_μ-N_e dependence occurs at a size (4.10^5) which is a factor of 5 smaller than that at which the size spectrum steepens (2.10^6). In the lower size region, the mean mass number seems to be independent of size since the experimental slope of N_μ-N_e dependence agrees with the prediction for a constant composition. The data suggests a pure proton composition above a shower size of 10^6.

These features can be understood in a model suggested by Chatterjee[7] in 1964, which is a modification of Peters' rigidity cut off model. In Chatterjee's model, the galactic component undergoes rigidity cut off at a critical rigidity of 3.10^5 GV and a pure proton extragalactic component becomes dominant at 2.10^6 GeV, well before the cut off energy for iron nuclei.

An essential feature of the model is that the mean mass number is not allowed to increase with energy in the region where the composition is changing, by bringing in the extragalactic protons well below the iron cut-off energy . The difficulty with this model is that, apart from the need to exactly match the two proton components to yield a smooth spectrum, the energy dependence of the anisotropy[8] is difficult to understand. Also,the JACEE proton spectrum does not show any steepening upto 6.10^5 GeV. The photo-disintegration model suggested by Hillas[9] in which nuclei are removed in the source itself at $\sim 10^5$ GeV/nucleon due to photodisintegration and protons suffer severe energy losses at a few times 10^6 GeV due to photo pion production can also explain the data since protons continue almost upto the iron cut-off energy. Again the anisotropy is difficult to understand in this model, if the knee in the primary spectrum is due to energy losses in the photo pion production process.

Incorporating the good features of the two models, we propose the following model. Nuclei are removed due to photodisintegration at an energy/nucleon of 7.5×10^4 GeV, as in Hillas' model. Upto this energy, the spectra of various components are, as given by JACEE measurements[10],expressed as K $E^{-2.68}$ dE, with K = 1.29,0.76,0.90,0.35 and 0.57 for mass numbers 1,4,14, 26 and 56. The iron spectrum is taken as the difference between the all particle flux from the Tien Shan experiment[11] (which agrees with the Grigorov all particle spectrum) and the sum of all components from JACEE. The spectral index of protons increases by 0.5 at 6.7×10^6 GeV due to leakage from the galaxy. The values of the critical energies are estimated by identifying the discontinuity of N_μ -N_e dependence at 4×10^5 as due to removal of iron nuclei and the steepening of the size spectrum at 2.10^6 as due to leakage of protons and using the scaling model with rising cross sections[12]. Cosmic rays upto $\sim 10^{10}$ GeV are of galactic origin. The aniso-tropy can be understood as due to leakage of protons. There is no need for a second component. The spectra of various components and the all particle spectrum according to this model are shown in Fig.2. The Tien-Shan spectrum is higher than the model since they use the same composition to derive the primary energy spectrum over the energy region where it is continuously changing according to this model. The mean mass number and percentage of iron as a function of primary energy (a) and size at 920 g/cm^2 (b) in this model are shown in Fig.3. It can be seen that the mean mass remains nearly constant even though the composition is continuously changing upto 4×10^6GeV ($N = 5 \times 10^5$) and becomes 1 beyond. The percentage of iron reaches a maximum of 32% at 4×10^6 GeV and then falls off to zero. The proton fraction also increases with energy. Obviously, this model explains the N_μ-N_e dependence. The size spectrum at 920 g/cm^2 expected from this model is compared with the KGF data in Fig.4(Curve b). The first three experimental points are corrected for detection efficiency of flat showers and shown as filled circle. The agreement is obvious. Curve (a) is for the same model, but the spectral index for all the components is 2.72 with intensities normalised at 100GeV/nucleon. Thus, the present model, with the spectra mentioned earlier, explains the KGF data.

Comparison with other experimental data

Estimates of the position of shower maximum, t_m, from measurements of pulse profile[3] and lateral structure of Cerenkov photons[4] in small showers have indicated iron-rich composition in the energy region 10^6-10^7GeV.The measurements of pulse profiles have been shown to be subject to the systematic errors[13,14] and thus may not be reliable. The values of t_m obtained from

lateral structure are systematically smaller than those from pulse profile meas-
urements suggesting that they also may be subject to systematics.Recent measu-
rements[15],[16] using large areas of photomultipliers and triggering with Ceren-
kov light itself,thus being relatively bias-free,are shown in Fig.5 along with
earlier measurements at higher primary energies,which do not seem to have such
systematic effects.It can be seen that these new measurements do not show the
abnormal elongation rate and do not require an iron-rich composition.In order
to see the change of composition in this model,accurate measurements over a
wide energy range from a single experiment are required.

The composition derived from delayed hadrons[5] relies heavily on Monte
Carlo simulations.Even though the authors paid careful attention to the details
of the simulation,some of the factors,such as the neglect of nuclear target
effects, a cut off energy of 3 GeV for hadrons in the simulations together with
the finding of Mincer et al[17] that low energy hadrons do produce large signals
at a surprisingly large rate,would result in a larger fraction of delayed had-
rons in both proton and nucleus initiated showers,thus reducing the requirement
of iron from 40% at 10^6GeV. Thus the present model,which predicts the iron abun-
dance to increase with energy,with a value of 25% at 10^6GeV,would be in agree-
ment with their data.The Tien Shan data on low energy muons[11],which requires
unchanging composition,is however difficult to understand in this model.

Conclusions

The composition model in which nuclei are removed at 7.5×10^4GeV/nucleon in
the source and proton spectrum steepens at 6.7×10^6GeV due to leakage from the
galaxy explains most of the EAS data.Study of anisotropy of suitably selected
mu-rich showers can distinguish between the photo disintegration and rigidity
cut off models,since the former does not predict any anisotropy for nuclei
near the cut off energies.

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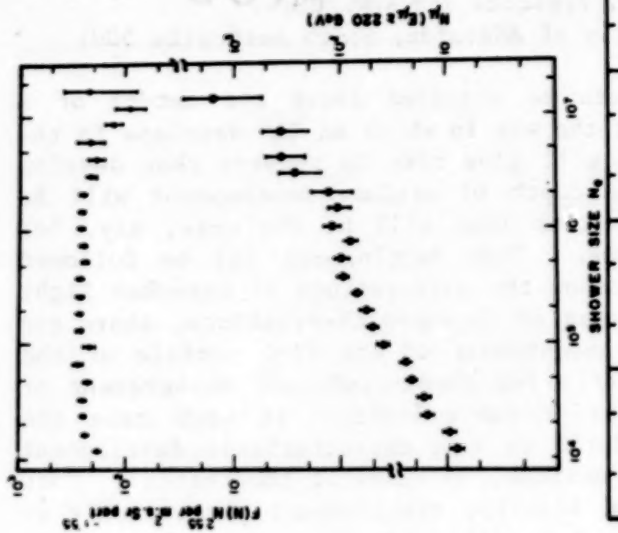
Fig.1
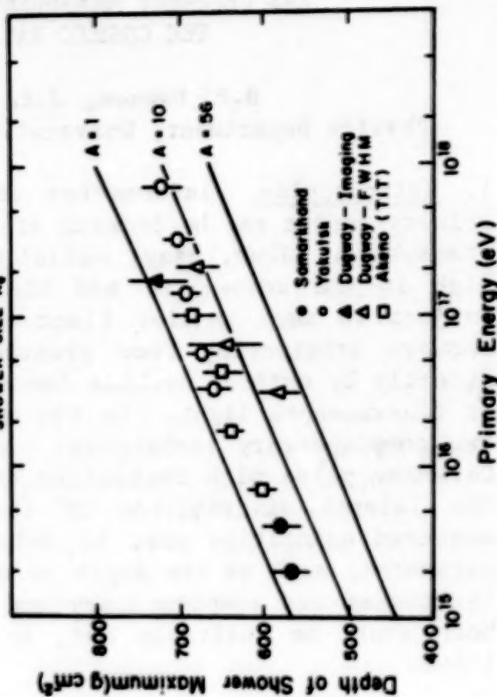
Fig.2

Fig.4

Fig.3

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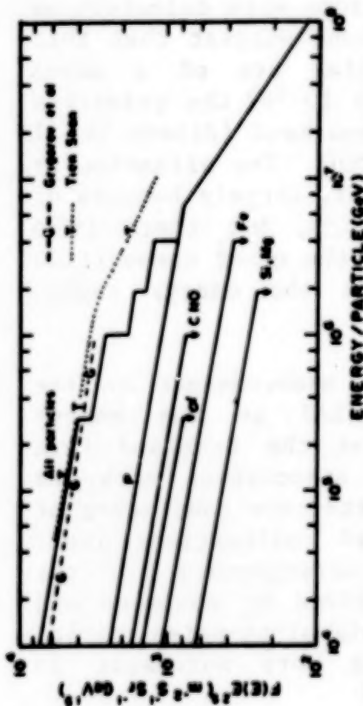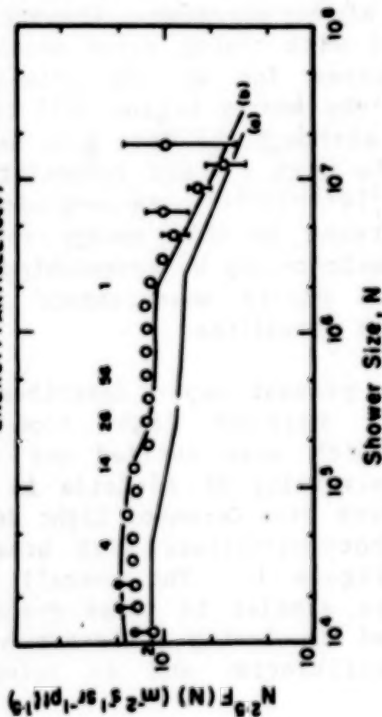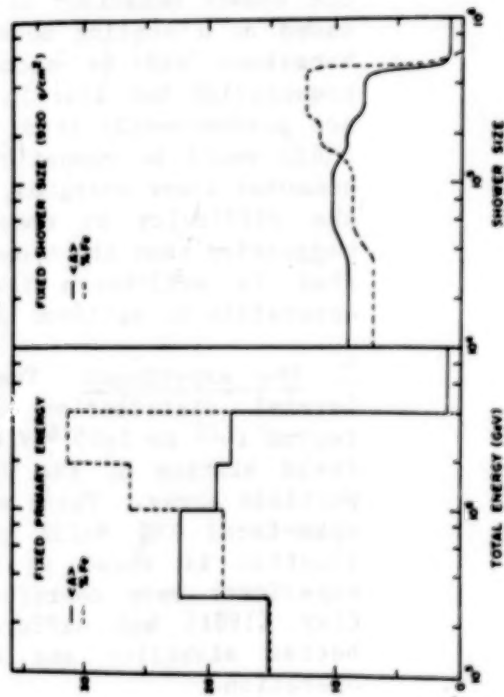
EAS CERENKOV MEASUREMENTS OF THE COMPOSITION OF
THE COSMIC RAY FLUX AROUND 10^16 eV

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1. Introduction   Information can be obtained about the nature of a
primary cosmic ray by looking at the way in which an EAS develops in the
atmosphere. Thus, heavy nuclei will give rise to showers that develop
high in the atmosphere and the depth of maximum development will be
subject to much smaller fluctuations than will be the case, say, for
showers originating from protons. This development can be followed
directly by optical methods based on the observations of Cerenkov light
or fluorescence light. In the case of Cerenkov observations, there are
two complementary techniques: measurement of the time profile of the
Cerenkov pulse with resolution of a few nanoseconds and measurement of
the lateral distribution of the Cerenkov light. In each case the
measured quantities must be related to some characteristic development
parameter, such as the depth of maximum, by means of theoretical. Both
techniques are complementary and ideally, simultaneous measurements on
both would be desirable but, so far little has been done along these
lines.

At the time of the Bangalore Conference it seemed clear that for
energies above about 10^{17}eV the depth of maximum changes slowly with
energy at an elongation rate of about 50 gcm^{-2} per decade but that in
the energy interval 10^{16}eV to 10^{17}eV the elongation rate becomes much
larger and, in the decade below 10^{16}eV , the depth of maximum is much
deeper in the atmosphere than would have been expected on the basis of
the shower behaviour at higher energies. Comparisons with calculations
based on a scaling model with rising cross sections suggest that this
behaviour can be accounted for if the primaries are of a mixed
composition but that in the energy region 10^{15} to 10^{16}eV the primaries
are predominently iron, although the data from Samarkand (Alimov et al
1983) would be compatible with a mixed composition. The situation at
somewhat lower energies, 10^{13}–10^{15}eV , is less clear, largely because of
the difficulty in observing in this energy region, but there is a
suggestion that the composition may be approaching the mixed composition
that is well-known from direct measurements in the energy region
accessible to balloons and satellites.

2. The experiment   The present paper describes measurements on the
lateral distribution of Cerenkov light from EAS in the energy
region 10^{15} to 5×10^{16}eV which were carried out at the Buckland Park
field station of the University of Adelaide in association with the
particle array. There were nine Cerenkov light detectors consisting of
open-faced EMI 9623B photomultipliers with broad collimation. Their
location is shown in figure 1. The overall arrangements for the
experiment were therefore similar to those described by Kuhlmann and
Clay (1981) but differed in having a better signal-to-noise ratio,
better stability and calibration and in being more automatic in
operation.

● FAST TIMING AND DENSITY
   DETECTOR
● DENSITY DETECTOR
X CERENKOV DETECTOR   XL
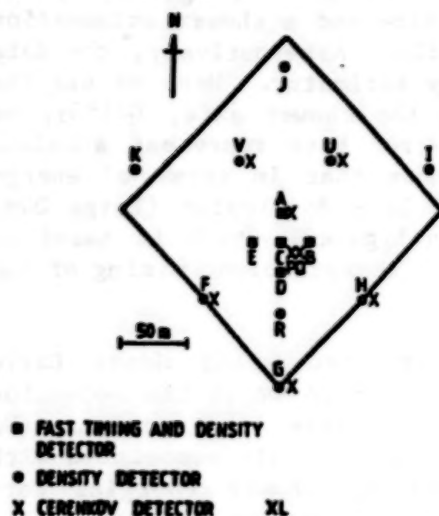
Figure 1: The Cerenkov lateral distribution array with the elements of the Buckland Park particle array used in the experiment.

The data were collected on clear moonless nights from October 1983 to March 1984. The Cerenkov recording system was triggered by the particle array which was also used to assign shower size, core location and arrival direction to each event. The triggering requirements were coincident signals corresponding to >2 particles m^{-2} in three of the central five (ABCDE) detectors. During 103 hr recording time, 9575 of these particle events were recorded. A total of 1279 of these events was selected for the purpose of measuring the Cerenkov lateral distribution. These showers arrived within 35 degrees of the zenith, were well-analysed in terms of the particle data and possessed at least 5 Cerenkov densities. This selection put a lower limit on the acceptable shower size at about 10^5 particles.

3. Analysis The use of the particle array for triggering is not ideal because there is necessarily an a priori selection bias towards late-developing showers. However, in the present case the selection biases associated with the particle array and its analysis procedures have been investigated by an extensive series of simulations. The data below are compared with model calculations in which the actual selection properties of the array and the analysis procedures are included.

In our interpretation of the measured lateral distributions we have used the calculations of Patterson and Hillas (1983b) which show that the shape of the lateral distribution within 150m of the shower axis is sensitive to shower development. Outside this radius the shape is not so sensitive, and the flux at a large radius is a measure of the energy of the primary particle. Ideally, this radius should be >200m, although for small showers it is often only possible to measure the lateral distribution out to ~150m. The flux at 150m is still expected to be a measure of the primary energy, but it will be subject to larger fluctuations than the flux at a larger radius. Patterson and Hillas suggest that the flux ratio $Q(50m)/Q(150m)$ (as suggested by Andam et al 1982) is the best measure of the shape of the lateral distribution inside 150m. They have related this parameter to H_m, the distance along the shower axis to shower maximum. We have fitted exponentials of the form $Q(r) = A \exp(-br/10^4)$ to our data for 25m<r<150m and have found them to be good fits. Indeed, in the majority of cases the exponential is also a good fit at larger radii. Using these fits, the ratio $Q(50)/Q(150)$ was found for each event and hence H_m. Knowing the zenith angles of the shower axes, depths of maximum were derived assuming an exponential atmosphere with a scale height of 8.0km.

The 1279 showers analysed in this manner have been binned in a variety of ways. Figure 2 shows the data plotted as depth of maximum (DOM) vs

the equivalent shower size at a depth of 1000 gcm^{-2} , $N_e(1000)$, the latter being calculated from the observed size and a shower attenuation length of 185 gcm^{-2} (Clay and Gerhardy 1982). Alternatively, the data may be binned in terms of a primary energy estimator. Here we use the Cerenkov flux at a distance of 150m from the shower axis, Q(150), as shown in figure 3. In both cases, the error bars represent standard deviations within the bins. Figure 3 shows that in terms of energy there is a bias towards the selection of late developing (large DOM) showers. This bias is not so obvious in figure 2 which is based on shower size. In this case there appears to be sufficient mixing of low energy showers to mask this effect.

The experimental distributions were interpreted using Monte Carlo simulations of proton and iron-produced showers in which the selection effects of the particle array were taken explicitly into account. (We believe that there is no significant bias specifically associated with the Cerenkov array). In these simulations, shower energies were selected from a broken-power-law energy spectrum between 10^{13} and 10^{18}eV. A depth of maximum for each shower was selected using the distributions given by Protheroe and Patterson (1984). Given a DOM, the sea level size of the shower was calculated by assuming the E_p - N_e(max) conversion given by Hillas (1983) and by using a shower development profile given by Patterson and Hillas (1983a). The simulated showers were then allowed to fall on the particle array using appropriate zenith and azimuth angle distributions and those showers which triggered the array were reanalysed for core position and shower size using the same shower analysis program as was used for the experimental data. Thus, provided that selection biases exist only for the particle array, the simulated data are now directly comparable with the experimental distributions. Figures 4 and 5 show selected simulation results. Here again the error bars represent standard deviations, which reflect the fluctuations in the DOM. The bias imposed by the array is especially evident in figure 5. The only showers observed below 10^{15}eV are late developing proton events.

In our attempts to match the experimental DOM vs $N_e(1000)$ distribution, a number of mixtures of proton and iron-produced showers was tried. It was found that a mixture of 95% Fe and 5% P produced a distribution consistent with the data (fig.2).This mixture also produced an agreement in the energy representation when a particular Q(150) - E_p assignment was made (fig. 3). It is noted that it is not necessary to invoke a changing composition across the energy range in question in order to match the data. Unfortunately there are not sufficient data in the high energy region to see the expected effect of a change in composition back to predominantly light nuclei above about 3×10^{16}eV. (e.g. Nagano 1983).

Thus we conclude that, having used simulations which include a realistic model of longitudinal development and the effects of particle array selection bias, we find that our data are consistent with a cosmic ray primary composition rich in iron over the energy range 3×10^{15} to 5×10^{16}eV.

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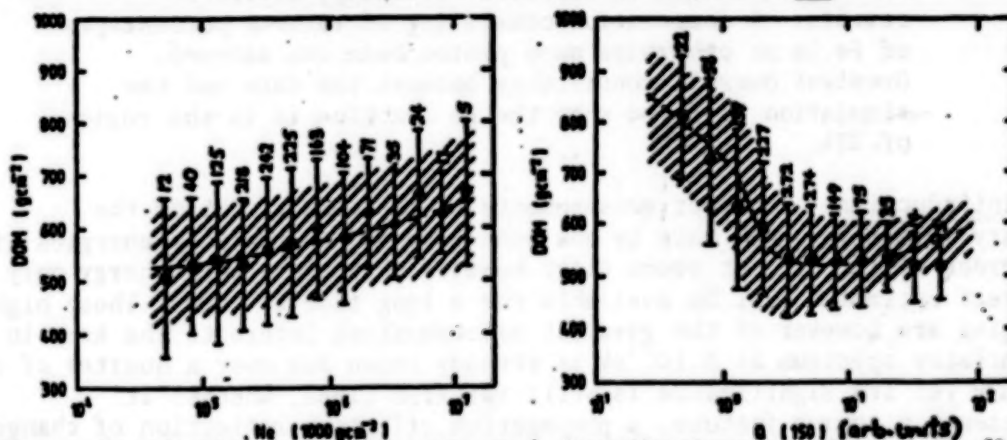
Figure 2 and Figure 3: Experimental distributions of DOM vs. N_e (1000) and primary energy estimator Q(150). Error bars in each figure represent standard deviations and the numbers indicate the number of events in each bin. The dashed lines and hatched regions represent the means and standard deviations of simulated data (95%Fe,5%P)(see text).
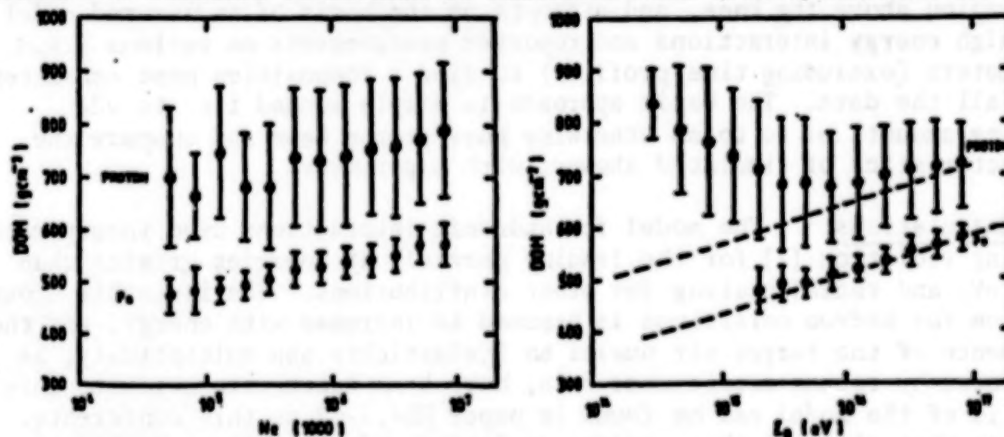
Figure 4 and Figure 5: Simulated distributions of DOM vs. N_e(1000) and primary energy E_p which take into account array selection biases. Error bars indicate standard deviations. The dashed lines in figure 5 represent the input distributions of mean DOM from Protheroe and Patterson (1984).

ELECTRON AND MUON PARAMETERS OF EAS AND THE COMPOSITION OF PRIMARY COSMIC RAYS IN $10^{15} \sim 10^{17}$ eV

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N85-34068

ABSTRACT

With a view to estimating the relative intensities of
protons and heavy nuclei in primary cosmic rays in the
energy region $10^{15} \sim 10^{17}$ eV, a systematic comparison
has been made between all available observed data on
various parameters of EAS with the results of simulation.
The interaction model used is an extrapolation of
scaling violation indicated by recent $\bar{p}p$ collider
results. A composition consisting of various percentages
of Fe in an otherwise pure proton beam was assumed.
Greatest overall consistency between the data and the
simulation is found when the Fe fraction is in the region
of 25%.

1. Introduction   Direct measurements of the composition of the
primary cosmic ray beam have by now been extended to particle energies of
the order of 10^{14} eV. It seems clear however that above this energy only
indirect estimates will be available for a long time to come. These high
energies are however of the greatest astrophysical interest; the knee in
the primary spectrum at $3 \ 10^{15}$ eV is already known for over a quarter of a
century yet its significance is still far from clear, whether it
represents a source feature, a propagation effect, a reflection of changes
in hadronic interactions or some combination of these. In particular
data from different types of experiments conflict so that, even in the
propagation effect scenario, it is problematical whether the knee at
$3 \ 10^{15}$ V represents the rigidity at which leakage effects start setting
in, or have already terminated [1]. The present report is confined to
the region above the knee, and attempts on the basis of an assumed model
for high energy interactions and reported measurements on various E.A.S.
parameters (excluding time profiles) to find a composition most consistent
with all the data. The basic approach is simple minded i.e. to add
varying amounts of Fe to an otherwise pure proton beam and compare the
characteristics of simulated showers with experiment.

2. Calculations   The model for hadronic interactions used incorporates
scaling violation [2] for the leading particle at energies greater than
$2 10^{13}$ eV, and radial scaling for other distributions. The inelastic cross-
section for hadron collisions is assumed to increase with energy, and the
influence of the target air nuclei on inelasticity and multiplicity, as
evidenced by recent accelerator data, have been taken into account; more
details of the model can be found in paper HE4.3-12 at this conference.
We note that although this scaling violation model has been adopted as a
plausible, and consistent, framework for the calculations it is not
above criticism [3].

Three dimensional Monte Carlo simulations for proton and Fe

OG 5.2-12

nucleus initiated events with primary energies in $10^{15} - 10^{17}$eV were carried out. Log-normal distributions in different quantities, with variances as determined by the simulations, and a primary differential spectrum of slope -3.0 were used to relate parameters at fixed shower size (as measured) with the simulations at fixed primary energy. In establishing longitudinal development profiles of electrons and muons when more than one primary species is present, for comparison with equi-intensity cuts, the approximate method described in paper HE4.3-12 was used.

The quantities investigated so far are the fluctuations in muon size $\sigma_{N\mu}/\langle N_\mu \rangle$, N_μ vs. Ne correlations, electron longitudinal development, muon longitudinal development and lateral distribution. This roughly is the order of their sensitivity to primary composition; the ratio $\sigma_{N\mu}/\langle N_\mu \rangle$ although it varies most is also however ambiguous in some regions, while the muon lateral distribution is almost independent of primary mass and will not be considered further here. The muon longitudinal development, as reflected in equi-intensity cuts is considered in greater detail in paper HE4.3-12 at this conference.

3. Results   The data on electron size equi-intensity cuts used were: Chacaltaya (550 gcm^{-2}) intensities 10^{-6}, 10^{-7}, 10^{-8}, 10^{-9} and 10^{-10}m^{-2} s^{-1} sr^{-1}. Tien Shan (690 gcm^{-2}) 10^{-6}, 10^{-7}, 10^{-8} and Akeno (930 gcm^{-2}) 10^{-6}, 10^{-7}, 10^{-8}, 10^{-9}, 10^{-10}. A comparison of these data with some results of the simulations (taking the coefficient in the integral primary
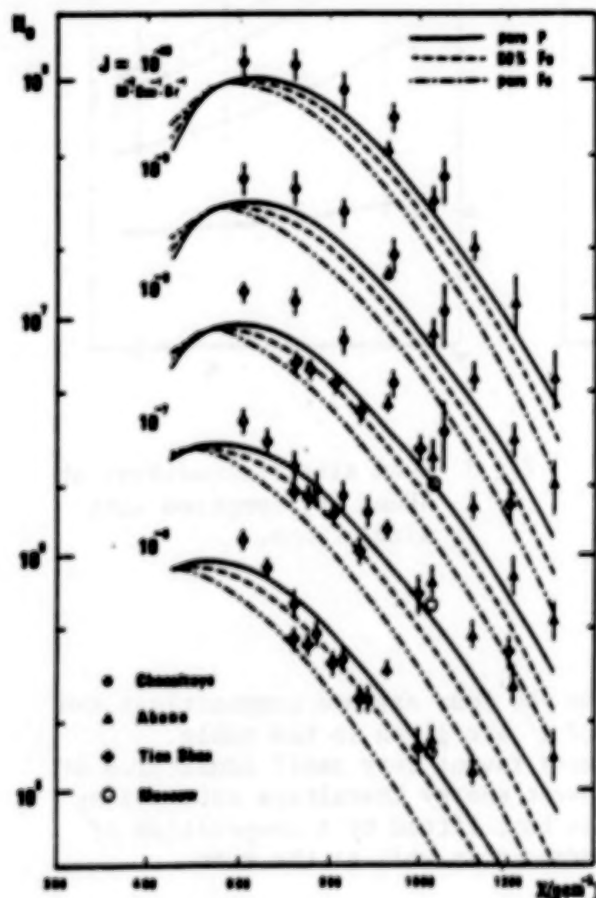
Fig.1 The longitudinal development of electrons from equi-intensity cuts for various compositions compared with observed points (A = 2.510^6)

spectrum $A = 2.5 \times 10^6$ [4]) are shown in fig.1. In the belief that the shape of the experimental curves may be more reliable than the determination of absolute sizes, a normalisation of the simulated curve i.e. a revision of A, to each experiment has been carried out by requiring the value of χ^2 (normalised), calculated using the data of the experiment and the simulated curve, to be a minimum (the variance in both the data and simulation results being allowed for). For each of the 3 experiments such minimum values of χ^2 have been obtained for each of 4 compositions i.e. pure protons, 25% Fe, 50% Fe and pure Fe.

Exactly the same procedure was carried out for the data on muon equi-intensity cuts: Chacaltaya at 10^{-8} and $10^{-9} m^{-2} s^{-1} sr^{-1}$, Tien Shan at 10^{-7} and 10^{-8} and Akeno 10^{-8} and 10^{-9}, each composition yielding 6 values of minimum χ^2 - some data are shown in fig.3 of paper HE4.3-12. Direct comparison was also made with N_μ vs Ne curves derived at Chacaltaya, Tien Shan, Akeno and Moscow - an example is shown in fig.2, and with the dependence of $\sigma_{N\mu}/\langle N_\mu \rangle$ on shower size as determined at Tien Shan, Akeno and Moscow - the comparison with Akeno data is shown in fig.3. In this way 7 further χ^2 values are obtained for each composition.
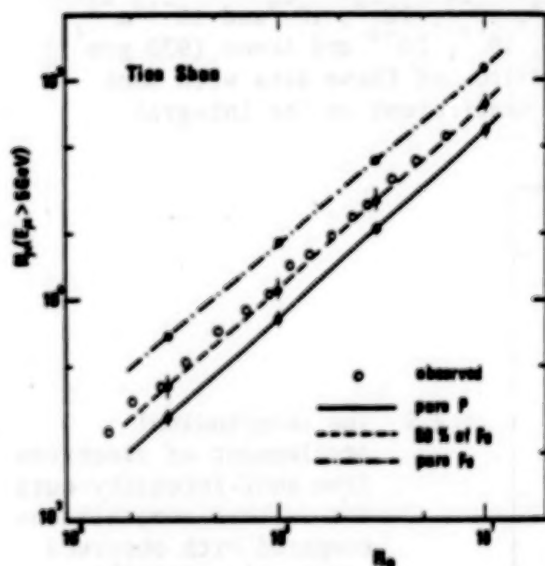
Fig.2 Comparison of N_μ vs N_e data
at Tien Shan [5] with
simulations.
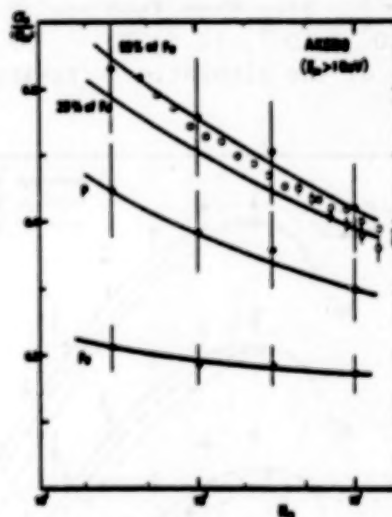
Fig.3 Muon size fluctuations at
Akeno [6] compared with
simulations.

The distributions in χ^2 for the four assumed compositions are shown in fig.4. The median values of χ^2 are given in the table. Generally the longitudinal developments favour very small admixtures of Fe, the major exception being the lowest energy Chacaltaya data - long known to be somewhat different; it is best fitted by a composition of pure Fe. The various N_μ vs N_e dependences as well as the muon

Composition	pure p	25%Fe	50%Fe	100%Fe
χ^2 median	0.96	0.62	0.82	7.51

fluctuations would generally favour somewhat more Fe. However, as the table indicates, when viewed overall a proportion of 25% is most favoured, if not very convincingly.

In the above considerations only the shapes of the equi-intensity curves were considered. If we turn to absolute values and take a coefficient $A = 3.75 \ 10^6$ (cf. $A = 2.5 \ 10^6$ in [4]) in the primary spectrum (this will lead to agreement between the electron size at shower maximum at $J = 10^{-10}m^{-2}s^{-1}sr^{-1}$ at Chacaltaya, where least sensitivity to the nature of the primaries exists, see fig.1), consistency with muon longitudinal developments, for any composition, can only be obtained by assuming systematic errors in muon size determinations. These are not serious for Tien Shan or Akeno(in magnitude $\leqslant 20\%$) but for Chacaltaya suggests overestimates of muon size up to a factor of 2. Adjusting observed muon sizes to be consistent with the intensity, values of χ^2 were again obtained for N_μ vs N_e relations, and $\sigma_{N_\mu}/\langle N_\mu \rangle$. The general effect is to favour somewhat more Fe than 25% but the difference is not very great.

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Fig.4 χ^2/N distributions

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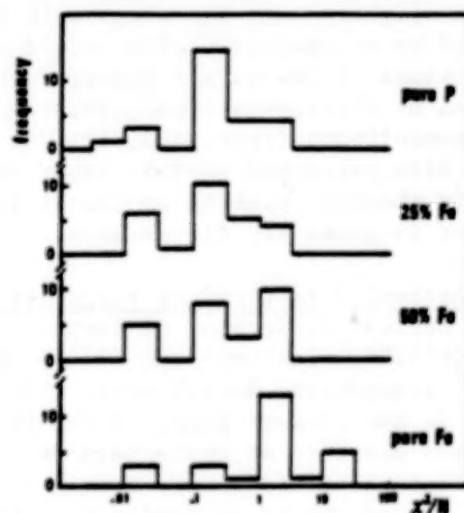
N85-34069

Arrival Directions of Large Air Showers,
Low-Mu Air Showers and Old-Age Low-Mu Air Showers
Observed at Mt. Chacaltaya

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ABSTRACT

Arrival directions of air showers with primary energies in the range
$10^{16.5}$eV to $10^{18.0}$eV show the first harmonic in right ascension(RA) with
amplitude of $2.7\pm1.0\%$ and phase of 13-16h. However, the second harmonic
in RA slightly seen for showers in the range $10^{18.0}$eV to $10^{19.0}$eV disap-
peared by accumulation of observed showers. The distribution of arrival
directions of low-mu air showers with primary energies around 10^{15}eV ob-
served at Chacaltaya from 1962 to 1967 is referred to, relating to the
above-mentioned first harmonic.

Also presented in this paper are arrival directions of old-age low-
mu air showers observed at Chacaltaya from 1962 to 1967, for recent in-
terest in gamma-ray air showers.

1. Arrival directions of large air showers

Arrival directions of large air showers observed at Mt. Chacaltaya
(16°20'52"S in latitude and 68°7'57"W in longitude, 5200m a.s.l. or 550
gcm^{-2} atmospheric depth) until 1979 were reported at the Paris Conference
(1). In the present paper we report on arrival directions of large air
showers observed at Chacaltaya until 1984. The air-shower array and the
detectors after 1979 were same as those described in the previous paper
(1). Procedures to determine the arrival directions(θ,ϕ) and the electron
sizes(N_e) as well as the uncertainties for showers observed after 1979 are
also same as those described in the previous report(1). The primary ener-
gies(E_o) of showers observed after 1979 were determined from a relation
between E_o and N_e at the maximum development(N_{emax}) given as $E_o(eV)=2.0\times
10^9(eV)\cdot N_{emax}$ described also in the previous report(1). N_{emax} was esti-
mated from N_e and the effective atmospheric depth where the shower was
observed($550gcm^{-2}\times sec\theta$), following the longitudinal development of elec-
trons determined at Chacaltaya(2).

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Table 1 and 2 show the results of harmonic analyses in right ascension of the arrival directions of showers with zenith angles smaller than 60°. In the tables, figures in upper row correspond to the first harmonic and those in the lower row correspond to the second harmonic. As is seen in tables 1 and 2, the first harmonic is predominant at primary energies in the range $10^{16.5}$eV to $10^{18.0}$eV as was seen for showers observed until 1979[1]. However, the second harmonic slightly seen for showers observed until 1979 with primary energies in the range $10^{18.0}$eV to $10^{19.0}$eV disappeared by including the showers observed until 1984.

Table 1.

Energy (E_0 in eV)	Number of showers	Amplitude (r in %)	Phase (in hour)	k_0	p(>r)	period
$10^{16.5}$-$10^{17.0}$	17477	2.7± .1	13.1±1.5	3.11	0.05	1981
		1.7± .1	11.2±2.8	0.61	0.55	-1984
$10^{17.0}$-$10^{17.5}$	12914	2.0± 1.1	15.5±1.7	2.21	0.11	1977
		0.9± 1.2	0.2±3.6	0.28	0.76	-1984
$10^{17.5}$-$10^{18.0}$	3372	4.9± 2.4	16.3±1.8	1.99	0.14	1977
		1.9± 2.4	10.0±3.5	0.30	0.74	-1984
$10^{18.0}$-$10^{18.5}$	593	6.6± 5.8	7.0±2.7	0.65	0.52	1977
		4.4± 5.8	10.0±3.5	0.29	0.75	-1984
$10^{18.5}$-$10^{19.0}$	117	6.0±13.1	12.2±4.4	0.10	0.90	1977
		17.8±13.1	2.0±2.4	0.93	0.39	-1984

Table 2.

Energy (E_0 in eV)	Number of showers	Amplitude (r in %)	Phase (in hour)	k_0	p(>r)	period
$10^{17.0}$-$10^{18.0}$	21534	2.7± 1.0	15.0±1.3	3.94	0.02	1964
		0.6± 1.0	8.8±3.9	0.19	0.83	-1984
$10^{18.0}$-$10^{19.0}$	1118	3.5± 4.2	2.7±3.3	0.35	0.71	1972
		6.2± 4.2	8.7±2.3	1.01	0.34	-1984
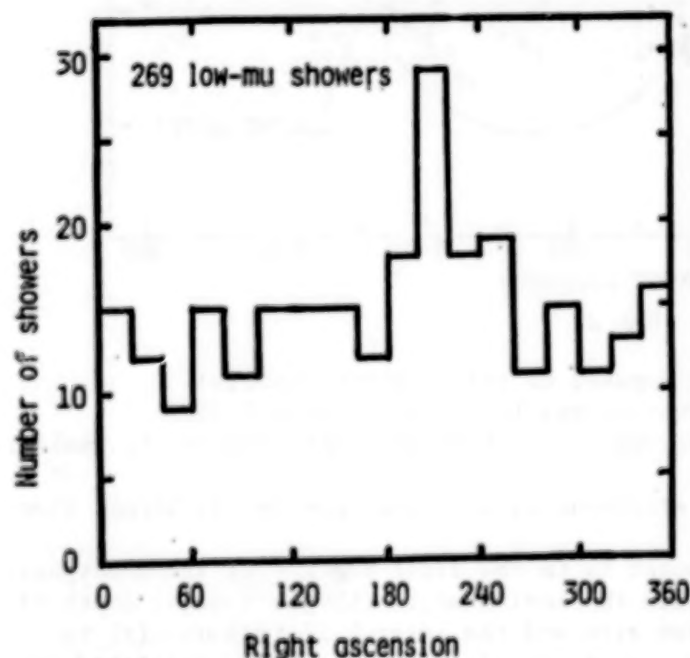
Fig. 1

2. Arrival directions of low-mu showers

Relating to first harmonic at primary energies in the range $10^{16.5}$eV-$10^{18.0}$eV, arrival directions of low-mu showers observed at Chacaltaya should be mentioned. Figure 1 shows the distribution of low-mu showers with zenith angles smaller than 60° along right ascension. The average size of the showers is about 3×10^5 and the proportion of the low-mu showers is about one thousandth of all showers. This figure was drawn in 1978 after the Calgary Conference in 1967 [3] by including all showers observed from 1962 to 1967. An excess of the

showers is observed between 180°(12.0h) and 260°(17.3h) in right ascension. At that time, we assumed that these low-mu showers were candidates of gamma-ray showers. However, these low-mu showers may be showers produced by primary protons which encountered the first interactions in the deep atmosphere or produced mainly neutral pions at the first interactions, referring to the argument described in section 3. Then, it is very interesting that the right ascension where the excess of low-mu showers are observed coincides with the phase of the first harmonic described in section 1 at primary energies in the range $10^{16.5}$eV to $10^{18.0}$eV, since that fact may be related with the composition of primary cosmic rays.

3. Arrival directions of old-age low-mu showers

Relating to the low-mu showers, it is worth while mentioning the arrival directions of old-age low-mu showers observed at Chacaltaya from 1962 to 1967. Arrival directions of these showers were plotted on the celestial sphere in 1967 as shown in figure 2 but was not published[4].
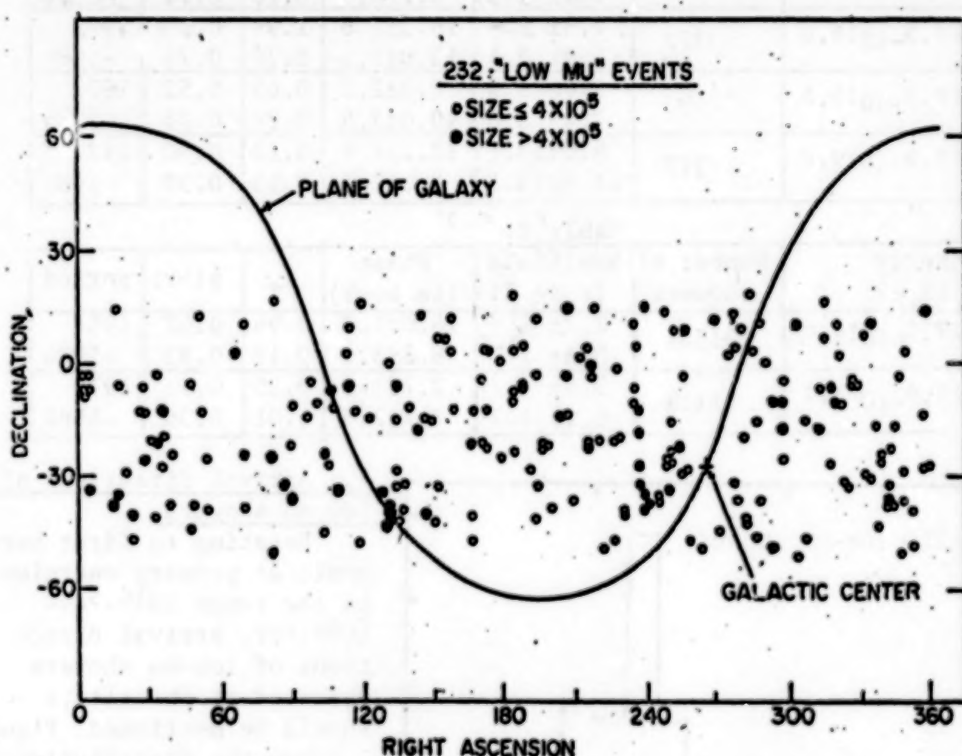
Fig. 2

The following criteria were imposed to select these showers:
(1) The zenith angle of shower is smaller than 37°($\sec\theta < 1.25$).
(2) The number of muons observed in the 60m² shielded detector is smaller than four.
(3) The expected number of electrons at the muon detector is larger than 2000/60m².
(4) The shower initiation point is in the first 80gcm⁻² of the atmosphere. The point is estimated from the zenith angle (550gcm⁻²×secθ: depth of observation), the electron size and the lateral distribution(s) by comparing the value of s with those of s for gamma-ray initiated purely electromagnetic showers. This is a criterion effective to select old-age showers produced probably primary gamma rays.

Areas in which the densities of arrival directions were several times higher than average are found near $(\alpha:135°,\delta:-40°),(240°\sim255°,-20°\sim-40°)$ and at some locations adjoining the blank area seen around $(10°,-20°)$. The first location corresponds exactly to that of Vera X-1(09h00m13.18s,$-40°21'25.3"$). The Adelaide group reported recently gamma-ray air showers from this X-ray source synchronized with period of the eclipsing binary [5]. There are some X-ray sources in the second location and a strong X-ray eclipsing binary X1700-377(3.4d period;17h00m32.70s,$-37°46'28.8"$) is neaby. Regarding to the third location, a high peak is seen at galactic latitude of $-60°$ to $-70°$ when the distribution of the arrival directions is examined in galactic latitude. The expected number of showers for this region is 13.5: the number observed is 27. For showers with N_e smaller than 4×10^5, the corresponding number are 10.4 and 25.

Stimulated by the interesting old BASJE results looked back upon the past and mentioned in sections 2 and 3, the BASJE group has begun the preparation for a new project to observe low-mu and gamma-ray showers with 32 $1m^2$ unshielded scintillation detectors located around the $60m^2$ muon detectors, among which 12 detectors are moved from the locations in the present large array, and to determine the arrival directions within an uncertainty of $1°$. The observation will be begun in the middle of 1986.

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(5) Protheroe, R. J. et al: Astrophys. J.(Letters) 280(1984)L47

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Anisotropy of Cosmic Rays of Energy 10^{15}eV to 10^{17}eV Observed at Akeno

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ABSTRACT

Anisotropy of cosmic rays is studied with EAS data by muon trigger.
The present results support those obtained by electron trigger which
suggest the significant anisotropy of second harmonics with phase around
100° in right ascension for showers of 10^{16}-10^{17}eV, and predominant
arrival direction of 230° in right ascension for muon-rich showers. It
seems that the phase of the first harmonics in the energy range below
10^{17}eV is about 300° in right ascension and the second harmonics near
6×10^{14}eV is statistically significant with an amplitude of $0.39\pm0.13\%$ in
direction of $83\pm10^{\circ}$ in right ascension.

1. Introduction

Anisotropy of arrival direction of cosmic rays in the energy range
larger than 10^{15}eV has been studied by various selection conditions on
air showers at the EAS Array of Akeno. The results by the trigger of
electron density were reported in the previous conference(Hara et al.
1981 and 1983a). In comparison, selection of air showers by
discriminating muon density(muon trigger) has the following advantage.
(1) Muon size N_μ is less fluctuating than electron size Ne as an
estimater of primary energy Eo. (2) The muon detectors are the
proportional counters in shielded room, of which response is less
affected by the temperature variation.

The EAS recorded by muon trigger(case I) is available since the
autumn of 1982 for Eo larger than 10^{15}eV. About 90,000 EAS's are
accumulated during two years of 1983 and 1984 and are analyzed for
anisotropy. Also presented in this paper is the result by another muon
trigger(case II), though whose result is preliminary. In this trigger,
the event rate per hour is recorded without detailed informations in each
detector of the array. The number of accumulated showers is 1.1×10^{6}
during half a year since June 1984.

2. Experimental condition and method of analysis

The EAS Array at Akeno(Hara et al. 1979) has nine muon stations,
with a threshold energy of 1 GeV. Effective area of each station which
consists of 50 proportional counters is 25 m^2. The following two
experiments have been performed with muon trigger.

In case I, when more than 4 muons hit each of 4 muon stations
located near the central area of the array, the EAS data are recorded.
The location of EAS core, zenith angle and electron size are determind
from electron data. Primary energy of each observed shower is estimated
from N_μ(Hara et al. 1983b).

In case II, the rate of air showers when more than 5 muons which are

spatially separated from each other hit one of 9 muon stations is
recorded. The median energy of these showers is found to be 6×10^{14} eV by
the analysis of AS data obtained by the calibration run with the same
trigger condition. The harmonic analysis is applied to get the anisotropy
after the correction of non-observation period by the method described in
Hara et al.(1983a). The anisotropy of muon-rich showers is studied in
case I as well as the anisotropy of total showers. The showers whose N_μ
to Ne ratio is 2 times larger than the mean value over all the showers
are defined as muon-rich showers.

3. Results and Discussions

Results of case I are presented in Table 1 for the total showers and
in Table 2 for muon-rich showers. The obtained amplitude and phase of
maximum intensity in right ascension are listed in the tables as well as
the number of showers N in each energy bin and the parameter of
reliability k where the probability of obtaining amplitude greater than r
from the uniform distribution is given by $w(>r)=\exp(-k)$ $(k=r^2N/4)$. Also
in Fig.1a and b, the phases of first and second harmonics are shown as a
function of primary energy respectively. In the figures, open circles
designate the results for total showers and closed circles for muon-rich
showers.

Table 1 (Case I. Total showers)

Eo	N	first harmonics			second harmonics		
		amplitude (%)	phase (degree)	k	amplitude (%)	phase (degree)	k
1.3×10^{15} eV	1480	3.1±3.7	46± 68	0.36	0.9±3.7	104±117	0.03
2.8	15461	0.6±1.1	284±104	0.15	0.9±1.1	93± 73	0.31
6.0	24558	1.6±0.9	313± 33	1.53	0.2±0.9	49±116	0.03
1.3×10^{16} eV	20289	1.7±1.0	290± 34	1.40	0.1±1.0	37±180	0.00
2.8	16129	2.2±1.1	299± 29	1.95	1.5±1.1	129± 21	0.94
6.0	9388	2.2±1.5	293± 39	1.09	3.2±1.5	72± 13	2.37
1.3×10^{17} eV	3203	1.9±2.5	288± 77	0.28	1.5±2.5	73± 47	0.18
2.8	758	5.9±5.1	340± 50	0.66	5.9±5.1	155± 25	0.65
6.0	127	7.2±12.6	103±100	0.16	15.3±12.6	144± 24	0.74

Table 2 (Case I. Muon-rich showers)

Eo	N	first harmonics			second harmonics		
		amplitude (%)	phase (degree)	k	amplitude (%)	phase (degree)	k
1.3×10^{15} eV	280	5.2±8.5	106± 93	0.19	16.5±8.5	149± 15	1.90
2.8	4842	4.4±2.0	215± 27	2.31	1.9±2.0	49± 30	0.45
6.0	8583	1.1±1.5	134± 81	0.25	1.4±1.5	62± 32	0.40
1.3×10^{16} eV	6421	2.5±1.8	260± 40	1.00	1.9±1.8	133± 26	0.60
2.8	4310	1.6±2.2	317± 77	0.28	0.7±2.2	80± 93	0.05
6.0	2462	2.8±2.9	14± 59	0.48	1.4±2.9	31± 60	0.11
1.3×10^{17} eV	737	10.6±5.2	317± 28	2.08	4.1±5.2	60± 36	0.32
2.8	112	5.5±13.4	342±139	0.08	6.2±13.4	90± 62	0.11

Although the present results are quite preliminary, the following
features can be noted.
(1) The first harmonics shows a roughly constant phase around 300° below

10^{17}eV. This is also seen in
Fig.2a, where thin circles
indicate the harmonic diagrams
for energy bin from 2.8×10^{15} to
1.3×10^{17}eV each and bold circle
indicates that of sum(amplitude,
1.59±0.47% and phase, $298^{O} \pm 17^{O}$
R.A. with k=5.63) for this
energy region.

(2) The second harmonics of
total showers appear to show a
tendency of maximum intensity at
phase $91^{O} \pm 28^{O}$ in right ascension
with amplitude of 0.50±0.48%
below 10^{17}eV, as seen in Fig.2b,
where the designations of
circles are the same in Fig.2a.

(3) Muon-rich showers have the
maximum phase of the first
harmonics near 220° below
10^{16}eV. Fig.3 shows the data for
energy from 2.8×10^{15}eV to
1.3×10^{16}eV and those sum
indicated by thin and bold
circles respectively.

The features (2) and (3)
are consistent with the results
obtained by electron
trigger(Kifune et al. 1985),
though present results are not
statistically significant. For
the feature (1), anti-sidereal
amplitude is 0.80±0.48% for the
same energy region which is
relatively small compared with
that of sidereal time variation.
The phase of about 300° is
different from the results
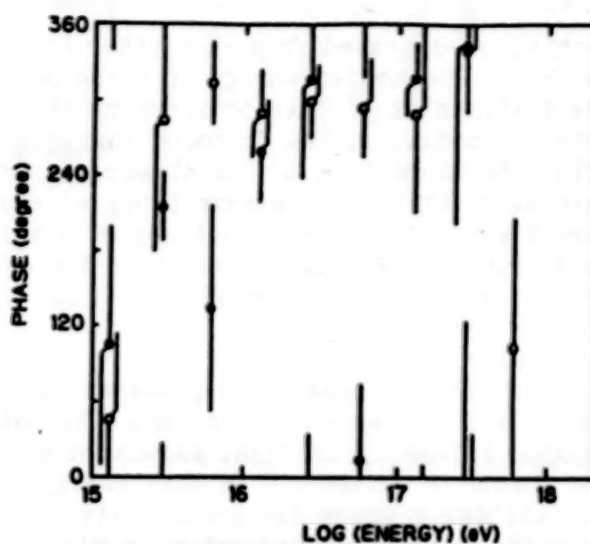
Fig.1a Phase of first harmonics
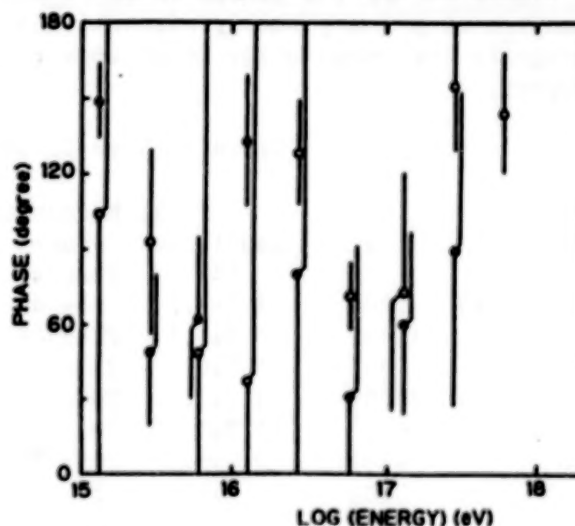
Fig.1b Phase of second harmonics
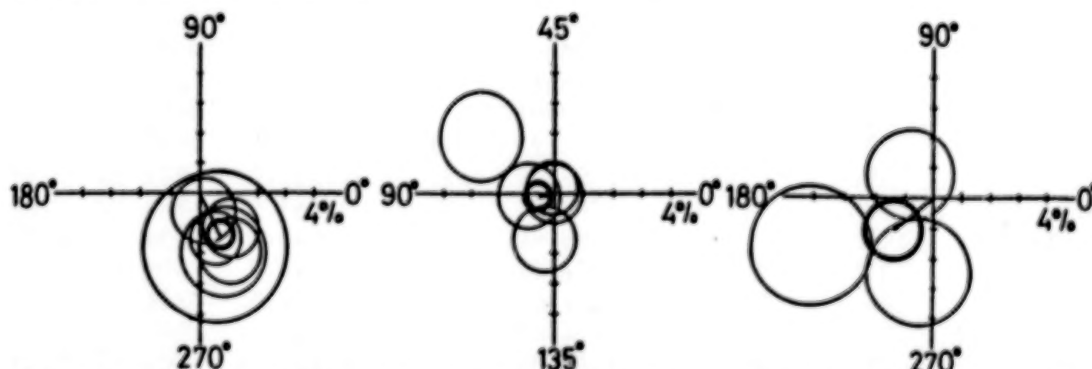
Fig.2a Harmonic diagram
of first harmonics for
total showers below
10^{17}eV.

Fig.2b Harmonic diagram
of second harmonics for
total showers below
10^{17}eV.

Fig.3 Harmonic diagram
of first harmonics for
muon-rich showers below
10^{16}eV.

obtained by electron trigger below 3×10^{16} eV, even if the magnitude of error is taken account of. One of the posibilities to explain this difference is to attribute it to the difference of triggering bias. If we presume muon size to be better estimater of primary energy than electron size, the data triggered by electrons include contaminations of events which have different primary energies in the same electron size bin, so the reliability of energy dependence of the anisotropy for the case of electron trigger is possibly less than that for muon trigger, especially for lower energy. However in present stage we need to examine this feature more carefully.

Table 3 (Case II)

Time variation	first harmonics			second harmonics		
	amplitude (%)	phase (degree)	k	amplitude (%)	phase (degree)	k
Sidereal	0.02±0.13	33±180	0.01	0.39±0.13	83± 10	4.14
Solar	0.10±0.13	142± 78	0.27	0.07±0.13	52± 57	0.13
Anti-sidereal	0.07±0.13	187±104	0.15	0.29±0.13	27± 13	2.39

The preliminary results in case II are presented in Table 3, and harmonic diagrams of first and second harmonics for sidereal time are shown in Fig.4a and b respectively. It appeares that second harmonics of sidereal time variation has statistically significant amplitude of 0.39±0.13% with k=4.14. The phase of maximum intensity is $83°±10°$. The similar results in the second harmonics are obtained by muon triggered data at 2×10^{15} eV conducted by Murakami et al.(1985) at Akeno.

Fig.4 Harmonic diagram of (a)first harmonics and (b)second harmonics, for 6×10^{14} eV in case II.

It should be noted that statistics are not sufficient at present, and observations are being continued to confirm the anisotropy of cosmic rays.

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ARRIVAL DIRECTIONS OF COSMIC RAYS OF E > .4 EeV

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ABSTRACT

The anisotropy of cosmic rays observed by the Utah Fly's
Eye detector has been studied. Emphasis has been placed on
examining distributions of events in galactic coordinates.
No statistically significant departure from isotropy has been
observed for energies greater than 0.4 EeV (1 EeV = 10^{18} eV).
Results of the standard harmonic analysis in right ascension
are also presented.

1. Introduction.   At the highest energies, the arrival directions
of cosmic rays are expected to begin to reveal their origins. In
this analysis the observed number of events is compared to the number
predicted for an isotropic distribution as a function of both galactic
longitude and sin (galactic latitude) for each energy interval, so
searches can be made for clustering in two dimensions. The event
distributions have also been fit to two different models for galactic
latitude dependence: 1. An excess of events from the general direction
of the galactic plane of the form $I_{(b)} = I_0[(1 - f) + f \exp(-b^2)]$ where
b is the galactic latitude in radians (1), and 2. A gradient with
respect to galactic latitude of the form $I_{(b)} = I_0(1 + s \cdot b)$, where b is
the galactic latitude in degrees. A similar analysis of the data is
performed in the two-dimensional celestial coordinates, and fits have
been made to the amplitude A and phase α_0 of the first harmonic of the
form $I_{(\alpha)} = I_0(1 + A \cos(\alpha - \alpha_0))$, where α is the right ascension.

2. Description of Analysis.   We report here the arrival directions
of extensive air showers observed by the Utah Fly's Eye detector,
situated at 41°N latitude, between the dates of Nov. 1981 and April
1985. A detailed description of the detector is reported in ref. 2.
Only data recorded on clear nights with no clouds higher than 10° above
the horizon were accepted. The total live time corresponding to these
"weather cuts" is 58.2 days. Further cuts on the data were made to
ensure well-measured tracks with good control over the error in
direction: the average error in zenith angle after cuts is σ = 3.8°.
Events passing all cuts were then binned in both galactic and celestial
coordinates for four energy intervals: 0.4 - 1.0 EeV, 1.0 - 3.0 EeV,
3.0 - 10.0 EeV, and > 10 EeV. All distributions were made in equal-
area bins of 5° in galactic longitude (or right ascension) versus 0.4
in sin latitude (or sin declination).

     Since the Fly's Eye can only operate on clear moonless
nights, the irregular pattern of observation times precludes the
assumption of uniform acceptance in right ascension made by experiments
running continously. The procedure used to calculate the number of

events expected as a function of galactic longitude and sin(latitude) from an isotropic distribution is outlined in this section. The distribution in celestial coordinates follows exactly the same prescription.

The absolute start and stop times for each data run have been recorded. For each 15 minute interval of detector on-time, the zenith angle for each bin of galactic coordinates is computed. Since the distribution in azimuth is uniform, the detector acceptance in zenith angle is the only quantity necessary to compute the acceptance times live-time product at each time interval and each pair of coordinates. Two different techniques have been used to find the acceptance as a function of zenith angle. The first is to use the Monte Carlo simulation of the detector. In principle, this allows an absolute rate determination in galactic coordinates, although only the relative rate was used for this analysis. The second technique uses the measured zenith angle distribution of the data itself to get the relative acceptance. An acceptance of 1 gives a flat distribution in $\cos(\theta_z)$, so measuring the deviation from a fixed number gives the θ_z dependence. The relative acceptance in zenith angle calculated directly from the data agrees very well with that predicted by the Monte Carlo simulation: the results reported here were shown to be insensitive to the distribution used.

The acceptance-weighted live times thus generated give the relative rates expected in each bin of galactic coordinates. The absolute normalization is then fixed by demanding that the total number of events predicted be equal to the total number of events observed in each energy interval. Deviations in the data from isotropy should then appear as local excesses (or deficits) of events compared with the number predicted.

Given the number of events observed and predicted in each bin, fits to various models for a possible anisotropy can be made. The number of events expected is weighted by the appropriate model-dependent factor (for example, $(1 + s \cdot b)$ to fit for a galactic latitude gradient s), the "expected" array is renormalized to preserve the same total number of events, and the joint probability for the observed to predicted distribution is calculated. Maximizing the probability with respect to variation in the parameters of the model (for example, s) gives the best fit to the data as well as the associated errors on the best-fit values of the parameters.
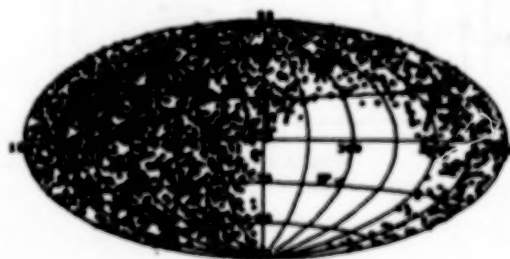
3. Results and Discussion. Figure 1 shows our acceptance in galactic coordinates from Monte Carlo events between 3-10 EeV. Note that the region between galactic longitude 240° to 0° and galactic latitude +30 to -90° are not visible to the Fly's Eye. Observed rates projected onto a single axis must, of course, be evaluated with this fact in mind.

Fig. 1. The Fly's Eye Acceptance.

The ratio of events observed to events expected as a
function of galactic latitude are shown in Fig. 2. Table 1 gives the
results for the two galactic models considered. Column a) shows fits
to a latitude gradient s of the form $(1 + s \cdot b)$; column b) shows the
fits to a galactic plane excess $(1 - f + fe^{-b^2})$ with b in radians. No
statistically significant deviations from isotropy are observed,
although the trend in the latitude gradient agrees with that observed
by other experiments (3). The data disagrees mildly with the analysis
presented in ref. (1) for the galactic plane excess model, at about
1 σ level. However, our inability to see a rather large region of the
galactic disk, in particular the galactic center, should be kept in
mind when interpreting these results.
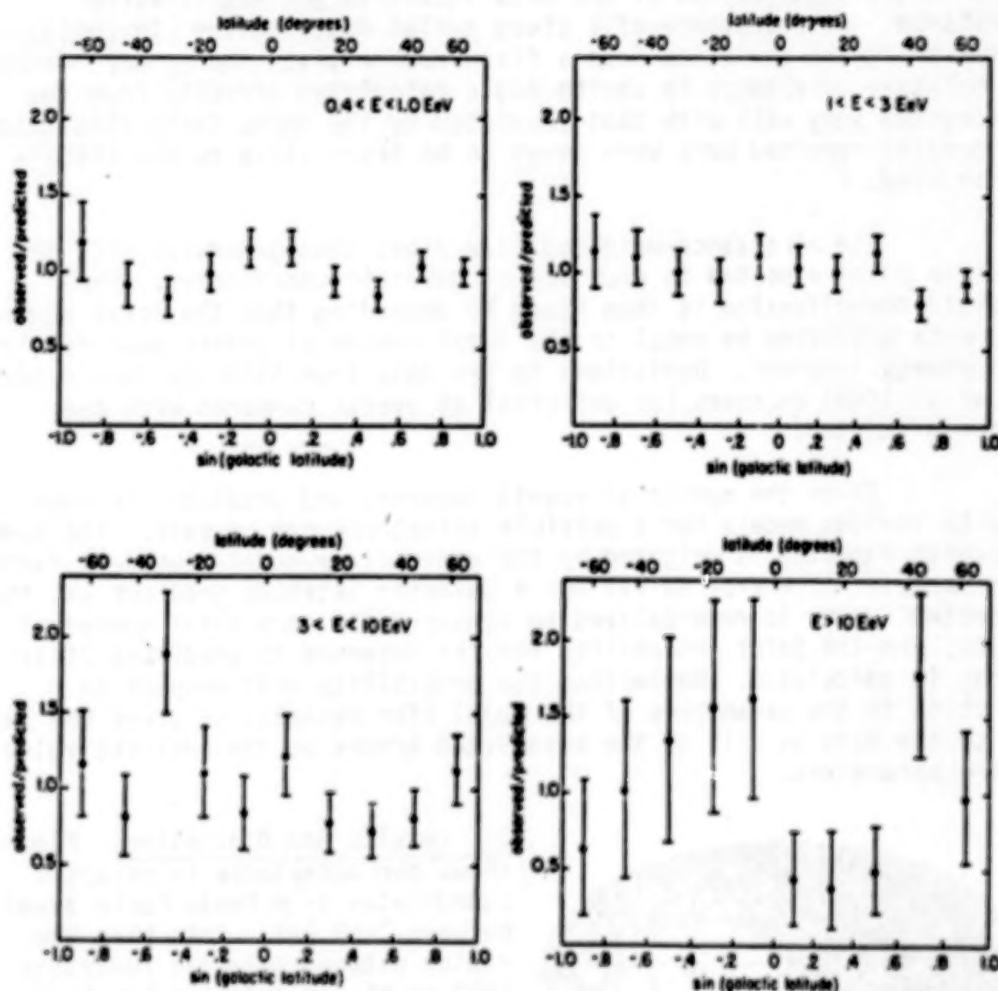
Fig. 2. Observed rates as a function of galactic latitude.

Table 1. Galactic latitude fits

Energy (EeV)	$\langle E \rangle$ (Eev)	Number of Events	a) Slope $s(10^{-3}/\text{deg})$	b) Galactic Plane Excess f
0.4-1.0	.64	760	-0.1 ± 1.6	0.06 ± 0.20
1.0-3.0	1.7	575	-1.5 ± 1.7	0.15 ± 0.21
3.0-10.0	5.0	170	-1.5 ± 3.0	0.0 ± 0.3
>10.0	18.8	45	0.6 ± 6.0	$0^{.5}_{-1.0}$

In celestial coordinates, the fits were made to the amplitude and phase of the first harmonic in right ascension, and are shown in Table 2. Here, there is some evidence for non-zero anisotropy, again in agreement with other experiments.

Table 2. First harmonic in right ascension

Energy (EeV)	Amplitude A	Phase α_0 (degrees)
0.4-1.0	$.15 \pm .08$	300 ± 30
1.0-3.0	$.07 \pm .08$	25 ± 80
3.0-10.0	$.25 \pm .16$	350 ± 40
>10.0	$.34 \pm .34$	290 ± 60

4. Conclusions.   If we believe that the cosmic rays above 1 EeV are predominantly protons from our own galaxy, then it is perhaps surprising that there is no evidence in our data for an enhancement from the general direction of the galactic disk. Certainly, more evidence on the composition of cosmic rays at this energy will be crucial to a real understanding of production sources and mechanisms. If a significant fraction of the observed cosmic rays are in fact galactic iron, or are "universal" extra-galactic protons, then the observed smoothness of the data would be reasonable.

Acknowledgment

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The sidereal anisotropy of cosmic rays around $3 \cdot 10^{15}$ eV observed
at a middle north latitude.

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ABSTRACT

The sidereal time variation of cosmic rays (median primary
energy : $3 \cdot 10^{15}$ eV) is investigated with air shower observations
at Akeno, Japan (900 m a.s.l.) which started in September 1981.
Air showers are detected by a coincidence requirement on several
muon detectors. The result obtained for three years is suggestive
of a big semi-diurnal variation (0.37 % in amplitude). On the
other hand, the diurnal variation is rather small than the semi-
diurnal one. The feature of the sidereal anisotropy supposed
from the present result looks quite different from that below
10^{14} eV.

1. Introduction.   In Bangalore Conference (1983), a review on sidereal
anisotropies in air shower observations was given by Linsley (1).   The
anisotropy beyond 10^{14} eV is still ambiguous, because of poor statistics
and also because most of results except that by Daudin et al. (2) are
not from air shower observations proper to the study of the sidereal
anisotropy. Recently we have carried out air shower observations at
Akeno, Japan (35°47'N, 138°30'E, 900 m a.s.l.) with the aim of studying
the sidereal anisotropy around $3 \cdot 10^{15}$ eV.

2. Observations.   The observations are made by using four muon detec-
tors (25 m², 50 proportional counters, 2 m thick concrete) being located
100∼200 m apart from each other. The detection of air showers is done
by the following triggering requirements. Fifty proportional counters
in each muon detector are divided into four groups of ten counters with
spacing of three counters. For detection of shower, at first, a coin-
cidence of incident particles is selected in the mode of "any two groups
out of four counter groups" in each muon detector, and next, another
coincidence is done in the mode of "any three- or four-fold coincidence"
among the coincidence signals fed from those four muon detectors.

The response function was obtained from the analysis of air showers
(1844 events) detected by the above-mentioned conditions. The result
(normalized integral response function) is shown in Fig. 1, where solid
points and open circles are values derived via the determinations of
muon size and electron size, respectively. In this analysis the follow-
ing points are noted. (1) The median primary energy is about $3 \cdot 10^{15}$ eV.
(2) The zenith angle distribution of detected air showers per solid
angle is proportional to $\cos^{5 \cdot 2} \theta$ (θ : zenith angle). (3) Although the
present triggering was doubted if it was favoured for detecting muon-
rich showers, no significant distinction from cases of electron trigger-
ing was found.

The continuous observations have been carried out since September
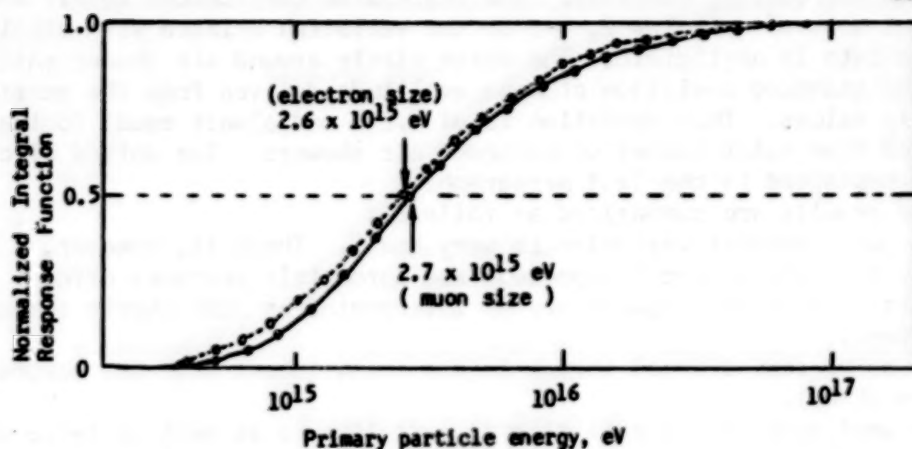
Fig. 1 Response function.

1981. In the following, a result obtained for three years until August 1984 is reported. The number of events is, in total, 2,237,059 showers observed in 962 days, after the rejection of days in which complete observations (with stable operation under constant condition throughout the day) were not fulfilled.

3. Results. Fig. 2 shows harmonic vectors in solar, sidereal and anti-sidereal time, averaged over three-year data without correction for barometric pressure effect or so on. The barometric pressure effect is of - 0.19 ± 0.03 % per mb. Open circles, P, shown in the figure are vectors expected from the barometric pressure effect. The other vectors, S, are variations of rate of single-particle incidences into four muon detectors including background radia-
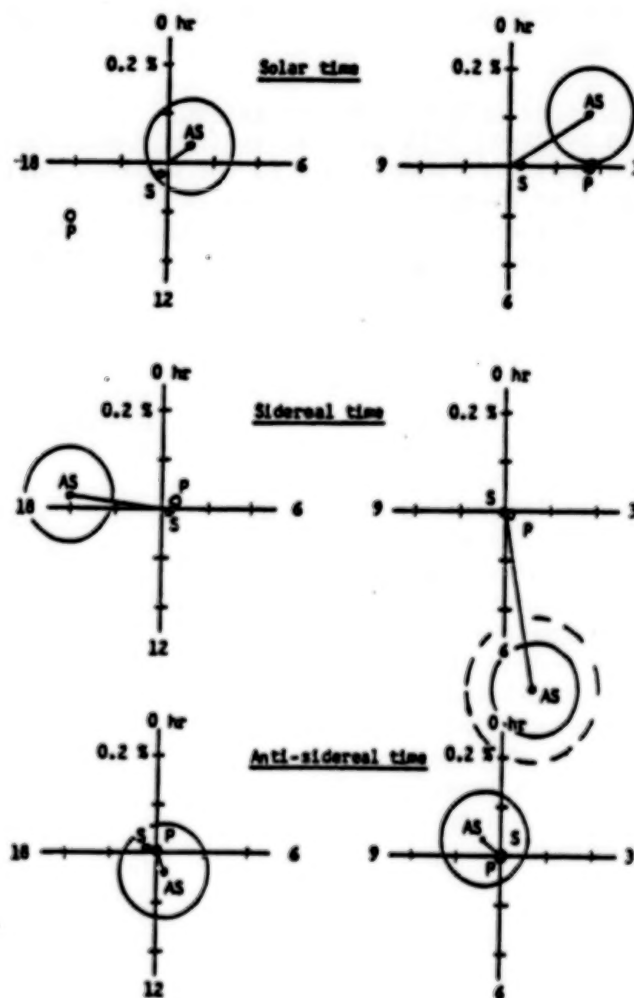
Fig. 2 Harmonic vectors.

tion from surrounding concrete. The regression coefficient to air shower
rate is at most of a factor 2, and so the variation related with single-
particle rate is negligible. The error circle around air shower rate AS
means the standard deviation of mean amplitude derived from the scatter
of hourly values. This deviation is of 0.1 % and almost equal to that
estimated from total number of recorded air showers. The dotted circle
will be explained in the last paragraph.

The results are summarized as follows :
(1) The solar diurnal variation is very small. There is, however, a dis-
crepancy from the vector P expected from barometric pressure effect.
Main part of this discrepancy may be interpreted as atmospheric tempera-
ture effect.
(2) The solar semi-diurnal vector is not inconsistent with the barometric
pressure effect.
(3) The amplitude of sidereal diurnal variation is as much as twice of
the standard deviation and so the existence of the diurnal anisotropy
is still hazy.
(4) The semi-diurnal vector in sidereal time is of 0.37 ± 0.10 % and
5.7 ± 0.8 hour. The existence of this vector will be discussed again in
the last paragraph.
(5) The diurnal as well as semi-diurnal variations in anti-sidereal time
are small.

4. Sidereal semi-diurnal variation. As mentioned above, it seems that
a big sidereal semi-diurnal vector is existent. Further analyses on this
anisotropy were made. One is the monthly shift of semi-diurnal vector on
solar time coordinate, as shown in Fig. 3. Except the shift from (Feb.,
Aug.) to (Sep., Mar.), the anti-clockwise turning of the vector with
month is very suggestive of the existence of the sidereal anisotropy.

However, another analysis shows
that the sidereal vector ob-
tained for each half-year is
rather widely distributed than
the scatter expected from
statistical fluctuation of
hourly values, as shown in
Fig. 4. The dotted circle in
Fig. 2 is corresponding to
this wide distribution of the
vector. Therefore, in order
to confirm the existence, it
may be necessary to wait for
more accumulation of the data.
At present we have no idea to
interpret why the vector
scatters so widely, although
we are trying to seeking for
the reason.

5. Summary. The sidereal
time variation around $3 \cdot 10^{15}$
eV was investigated with air
shower observations at Akeno
which started in September
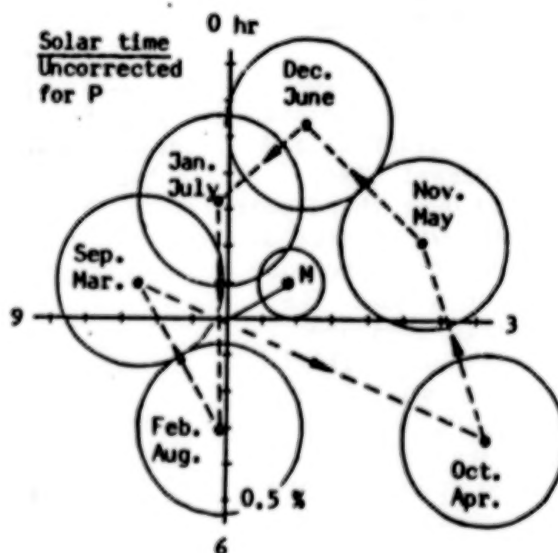
Fig. 3 Monthly vector of semi-
diurnal variation in solar time.

1981. The result obtained for three years gives a big semi-diurnal vector in sidereal time, 0.37 ± 0.10 % and 5.7 ± 0.8 hour. Although we need to accumulate more data in order to confirm the existence, it is very interesting that the semi-diurnal vector seems bigger than the diurnal vector, because the diurnal vector has been confirmed to be bigger than the semi-diurnal vector at north latitudes in the region below 10^{14} eV.

Although the above semi-diurnal vector was given with the standard deviation estimated from the fluctuation of hourly value, if we consider the wide distribution of the vector obtained for each half-year, the statistic for confirming its existence is still unsufficient (now the significance level = 1 %).

a : Sep. 1981 - Feb. 1982
b : Mar. 1982 - Aug. 1982
c : Sep. 1982 - Feb. 1983
d : Mar. 1983 - Aug. 1983
e : Sep. 1983 - Feb. 1984
f : Mar. 1984 - Aug. 1984
M : Sep. 1981 - Aug. 1984

Fig. 4 Distribution of sidereal semi-diurnal vector for each half-year.

The barometric pressure effect is explainable mainly with longitudinal development of muon size.

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ARRIVAL DIRECTION DISTRIBUTION OF COSMIC RAYS OF ENERGY > 10^{18} eV

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ABSTRACT

The Haverah Park air-shower experiment recorded over 8500 events with primary energy > 10^{18} eV between 1963 and 1983. An analysis of these events for anisotropies in celestial and galactic co-ordinates is reported. No very striking anisotropies are observed.

1. Introduction. Seven years ago the Haverah Park group (Edge et al 1978) published a detailed analysis of the arrival direction distribution of cosmic rays above 6×10^{16} eV. Since that publication there have been numerous 'up-dates' reported in conference proceedings and reviews. In this report we concentrate on the cosmic rays above 10^{18} eV where additional running has enabled us to increase our data from 4202 events (Edge et al 1978) to 8565. The additional data have been recorded with the same angular resolution as in the earlier work (rms variation in solid angle $< 10^{-2}$ sr); the energy resolution has been slightly improved by the addition of $3 \times 2.25 \, m^2$ detectors at 1 km from the array centre. We describe here the results of an analysis in celestial and galactic co-ordinates; fuller details will be reported elsewhere.

2. Harmonic Analysis in Right Ascension. The results of an harmonic analysis in right ascension over the declination range $90 < \delta < -6^{\circ}$ are given as a function of energy in Table 1. Following our previous practice the data are divided in energy $1 - 2 \times 10^{18}$ eV (E5), $2 - 4 \times 10^{18}$ eV (E6), $4 - 32 \times 10^{18}$ eV (E7,8,9) and $> 3.2 \times 10^{19}$ eV (E10). For brevity the notation E5 etc. will be used here. The first and second harmonics are given. Only amplitude uncertainties are quoted; probabilities of those amplitudes arising by chance from a random distribution equal $\exp(-k_0)$ and the phase uncertainty is $57.3/(2k_0)^{\frac{1}{2}}$ degrees, where $k_0 = r^2 n/4$ (Linsley 1975).

Table 1

	from Edge et al (1978)				Present Work			
	n	r_1%	θ_1°	k_0	n	r_1%	θ_1°	k_0
E5	2832	6.3 ± 2.7	50	2.83	5764	4.4 ± 1.9	67	2.76
E6	978	7.9 ± 4.5	37	1.52	1939	3.7 ± 3.2	17	0.65
E7,8,9	364	7.9 ± 7.4	280	0.55	812	5.7 ± 5.0	272	0.66
E10	28	57 ± 27	163	2.27	50	42 ± 20	179	2.16
		r_2%	θ_2°			r_2%	θ_2°	
E5	2832	3.0 ± 2.7	169	0.64	5764	2.7 ± 1.9	175	1.01
E6	978	11 ± 5	71	2.74	1939	4.3 ± 3.2	80	0.89
E7,8,9	364	18 ± 7	75	2.95	812	13 ± 5.0	83	3.59
E10	28	25 ± 27	59	0.45	50	12 ± 20	166	0.18

It is disappointing to report that the doubling of the Haverah Park data has led to a decrease in all of the amplitudes above 10^{18} eV. Of the 8 amplitudes listed the significance, as measured by k_o, of only 3 have increased. However the most significant amplitude of the new set was also the most significant of the original set: the 2nd harmonic in the energy bin E7,8,9 now has a probability of arising by chance of 2.8%. For 371 events in a similar energy range $(5 \times 10^{18} - 4 \times 10^{19}$ eV) the Yakutsk group find $r_2 = 7.6 \pm 7.3\%$ at $\theta = 114^{\circ}$ (Efimov et al 1983). The joint amplitude (n = 1183) is $r_2 = 11 \pm 4\%$, $\theta = 89^{\circ}$ with a chance probability of 2.8%.

The probability that the observed sets of 8 k_o's arise by chance from a random distribution has risen from 3% to 10%.

3. Analysis in Galactic Co-ordinates. In 1981 we introduced an analysis in galactic latitude from which a series of gradients of observed number/expected number as a function of galactic latitude was obtained (Astley et al 1981). The initial analysis was with a data base intermediate in size between that discussed in Edge et al (1978) and that now available; a S-N assymetry was claimed. The gradients given by Lloyd-Evans and Watson (1982) are listed together with the new gradients in Table 2. A correction to the binning algorithm used in calculating the gradients has been made and about 25% more data has been added above 10^{18} eV. The gradients are compared with results from other experiments in Figure 1.

The Haverah Park gradients show deviations from expectation significant at the 4% level $(\chi_8^2 = 1.97)$ and in addition (ignoring the most energetic (extragalactic?) events in E10) there is a clear tendency for the gradients to fall and then change sign as the energy increases. However there are strong systematic differences between the various experiments, none of which are consistent with the above gradients, for which no satisfactory explanation has yet been found.

4. Discussion. Wdowczyk and Wolfendale (1984) in an interesting discussion of cosmic ray anisotropy have suggested that the observation of an S-N gradient above 10^{18} eV is an artefact arising from the limited galactic latitude coverage of the Northern Hemisphere experiments.

Figure 1
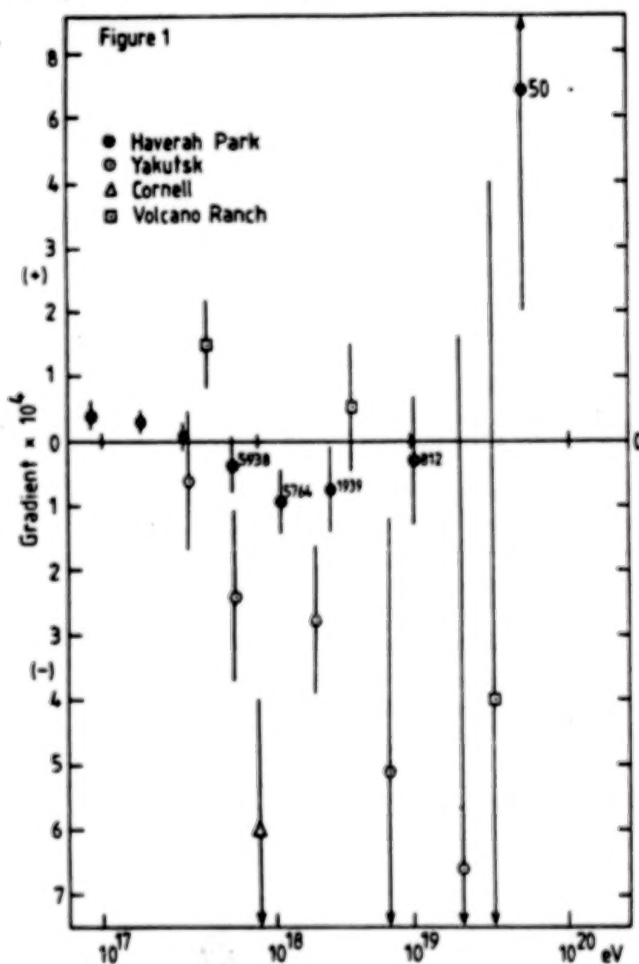
Table 2

| Energy interval | Lloyd-Evans & Watson (1982) | | Present Work | |
	n	gradient $(x\ 10^4\ deg^{-1})$	n	gradient $(x\ 10^4\ deg^{-1})$
E1	18829	$-1\ \pm\ 3$	18829	3.9 ± 2.4
E2	39982	$-2\ \pm\ 2$	39982	3.2 ± 1.6
E3	20635	$-4\ \pm\ 3$	20635	0.7 ± 2.2
E4	5938	-8.5 ± 4.3	5938	-3.6 ± 4.1
E5	4349	$-13\ \pm\ 5$	5764	-9.2 ± 4.1
E6	1499	$-16\ \pm\ 9$	1939	-7.5 ± 7.0
E7,8,9	610	$-22\ \pm13$	812	-3.3 ± 10
E10	38	$92\ \pm85$	50	66 ± 47

They propose instead that the data should be tested against a model which invokes a galactic plane excess and which predicts that the angular width of the galactic plane as seen in cosmic rays should shrink slowly with increasing energy.

The prediction of this model in which it is suggested that

$$I(b) = I(0)\left[(1 - f_E) + f_E \exp(-b^2)\right]$$

is compared with the data in Figure 2 for f_E, the galactic latitude enhancement factor, = 0.3 (Wdowczyk and Wolfendale 1985, Figure 1(d)). There is some evidence for a galactic plane enhancement.

We have investigated the galactic plane enhancement directly by comparing the number of events within $\alpha \pm 5^o$ of the galactic plane for the declination range $61.6 < \delta < -6^o$. For bins E5, E6, E7,8,9 the observed number of events was 268, 93 and 36 while 250, 83 and 36 were expected. There is clearly no significant evidence of enhancement.

Figure 2 E7,8,9
N = 812
Curve: Wdowczyk and Wolfendale (1984)
Gradient, ----- = $-(3.3\pm10)\times10^4$

In Figure 3 we compare the first harmonics of Table 1 with the predictions of Hill and Schramm (1985). The best estimate of the amplitude, s, (Linsley 1975) is shown together with 95% and 5% confidence levels. The predictions are derived from a model in which cosmological and bright
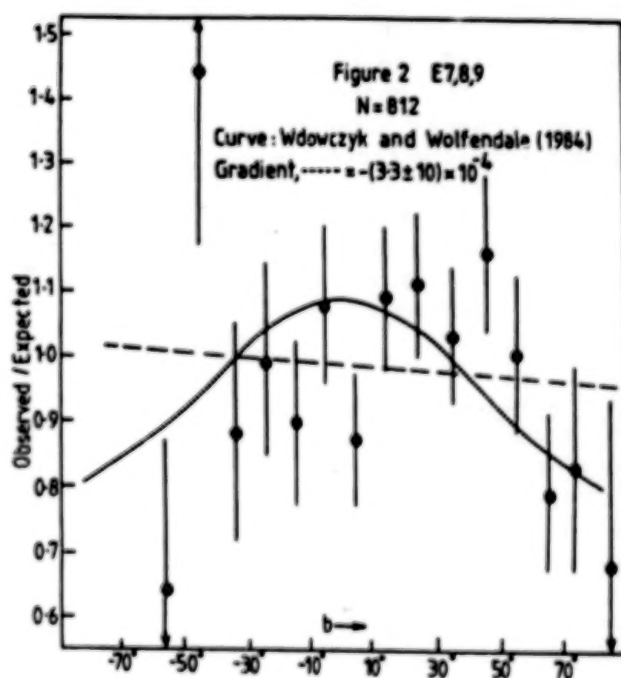
local extragalactic source fluxes
are combined. The injection
spectrum slope $\gamma = 2.0$ favoured
through their fit of spectrum
data predicts rather higher
anisotropies above 5×10^{18} eV
than are observed.

5. Conclusion. High energy
cosmic rays ($E > 10^{18}$ eV) are
remarkably isotropic. In
particular we remind the reader
that above 3.2×10^{19} eV (50
events) there is no evidence
for a galactic plane aniso-
tropy but there is some
evidence for an anisotropy of
$(40 \pm 20)\%$ in a direction
nearly normal ($\alpha = 180^\circ$) to
the galactic plane. Of the
8 events above 10^{20} eV which
we have observed, 4 are more
than 40° above the galactic
plane.
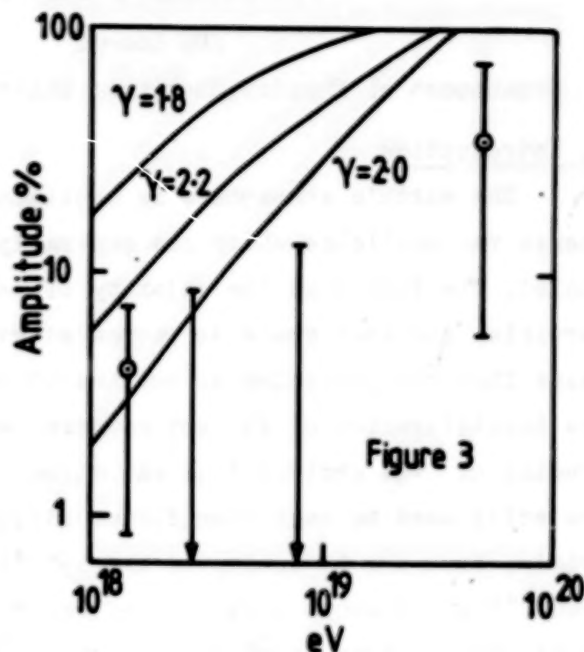
Figure 3

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OBSERVATION OF ARRIVAL TIMES OF EAS
WITH ENERGIES $\geqslant 6 \times 10^{14}$ eV

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1. Introduction

The earth's atmosphere is continually being bombarded by primary
cosmic ray particles which are generally believed to be high-energy
nuclei. The fact that the majority of cosmic ray primaries are charged
particles and that space is permeated with random magnetic fields,
means that the particles do not travel in straight lines. This makes
the identification of distant sources very difficult. Nevertheless,
studies of the arrival time and direction distribution of cosmic rays
are still used to seek significant information on problems of their
origin. From the beginning of the 1950's to the middle of the 1960's
about 50 experiments were carried out to study the arrival directions
of EAS with energy range from about 10^{14} to 10^{17} eV. Linsley and
Watson (1) summarised the results of these experiments and gave a
review at 15th Cosmic Ray Conferece.

On the other hand, the arrival time distribution of EAS may
also transfer some information about the primary particles. Actually,
if the particles come to our earth in a completely random process,
the arrival time distribution of pairs of successive particles should
fit an exponential law. This is derivable from Poisson's distribution.
Several groups (2,3) have reported a non-random component in the
arrival times of EAS with $E > 10^{15}$ eV, but others(4) did not find it.

The work reported here was carried out at Sydney University
from May 1982 to January 1983. The results are discussed and compared
with that of some other experiments.

2. Experiment System

This experiment work was carried out by using the Sydney
Small Air Shower Array. This sea level array has been described in
detail elsewhere(5). The array is composed of four fast timing
scintillators arranged as a 25m[25m horizontal square with four
triggering scintillators in a 4m[4m square in the same plane as the
fast timing scintillators. The triggering scintillator square is close

but not at the centre of the fast timing square. Pulses from the
scintillators are sent via fast rise time coaxial cables to the
recording electronics which is in an air conditioned hut with the
triggering scintillators. The recording electronics uses NIM/CAMAC
System. A master trigger pulse is produced if three out of four of
the triggering scintillators receive shower particles. Showers are
analysed in a desk-top computer which is employed to control the
recording system. The shower direction is found by a weighted least-
squares fit of a plane shower front to relative arrival time of each
detector. Then, using the maximum likelihood method to estimate the
shower size and core position. Finally, the celestial coordinates of
the incident direction of the event is found out. The rate of analysed
showers is 127 per day or one every 11.3 minutes on average. The time
needed for the full analysis is about 30 seconds.

3. Analysis and results

The data discussed here were obtained in the period from May 27
in 1962 to January 12 in 1983 at the campus of Sydney University
(latitude $35°$s). During this period more than 23000 showers were
recorded. The data are analysed in two different ways as follows.
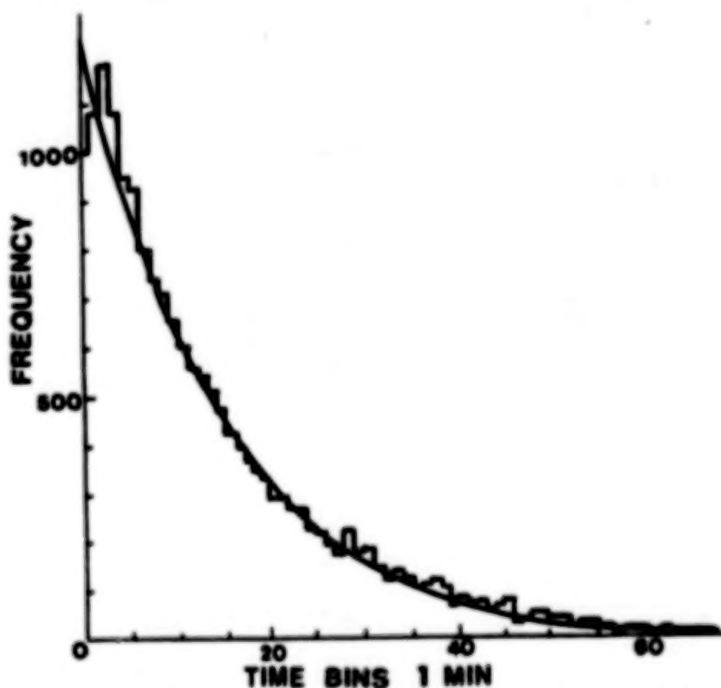
Fig. 1 Cosmic ray arrival time distribution

Firstly, all the data are used to plot the arrival-time
distribution of the events, that is, the distribution of time-separation
t between consecutive events on a 1 minute bin size (Fig. 1). The smooth
curve shows the expected exponential distribution of the arrival times
assuming that the time of occurrence of the events is completely random:

$$n = N_0(e^{-\lambda t_1} - e^{-\lambda t_2})$$

where λ is the average number of events per unit time. As can be seen

from Fig. 1, the observation data are compatible with random
expectation. After adding the estimated losses for the observation
data, no deviations are greater than 3σ. So that no experimental
evidence for abnormal behaviour in the inter shower arrival time
distribution has been found.

Then, the data are analysed with respect to the sidereal time
variation. Since the experiment was interrupted occasionally for
maintenance and by power failures, some allowances for this
interruption must be made before the analysing. After rejecting
certain numbers of events from those "over-exposure" time intervals,
the run time for every sidereal hour interval is unified. The data
are analysed by using the "random walk" harmonic method and the results
are:

the fractional amplitude $r = (1.9 \pm 1.1)$ %,
the probability of observing an amplitude $\geqslant r$ $p = 0.21$,
the phase of maximum $\psi = 74° \pm 33°$.

To compare these results with that of the experiments summarised
in Ref. (1), they are plotted together in Fig. 2 (after Kiraly et al
(6)). the value of p of the present experiment sits at the middle of
Fig. 2 (1), and the value of ψ just falls in the gap of the old data
in Fig. 2 (2). If anything this confirms the isotropy of arrival
directions.
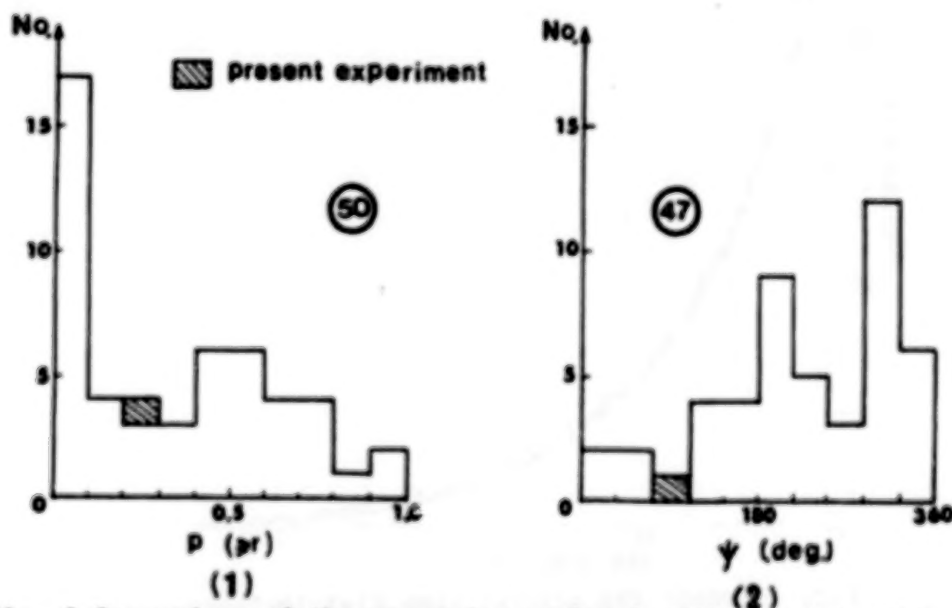
Fig. 2 Comparison of the present experiment with the data of Ref. (1).
The ordinates are the frequencies and the circles contain
the numbers of experimental sets contributing to the data
(excluding the present experiment).

The data are also tabulated on Mercator Projections and a series
of chi-squared tests is applied. The results are shown in Fig. 3. The
largest value of χ^2 for the tabulation is 57. The probability that χ^2
should have exceeded this value for one or more of eight independent

OG 5.3 - 8

Mercator Projection of Celestial Sphere
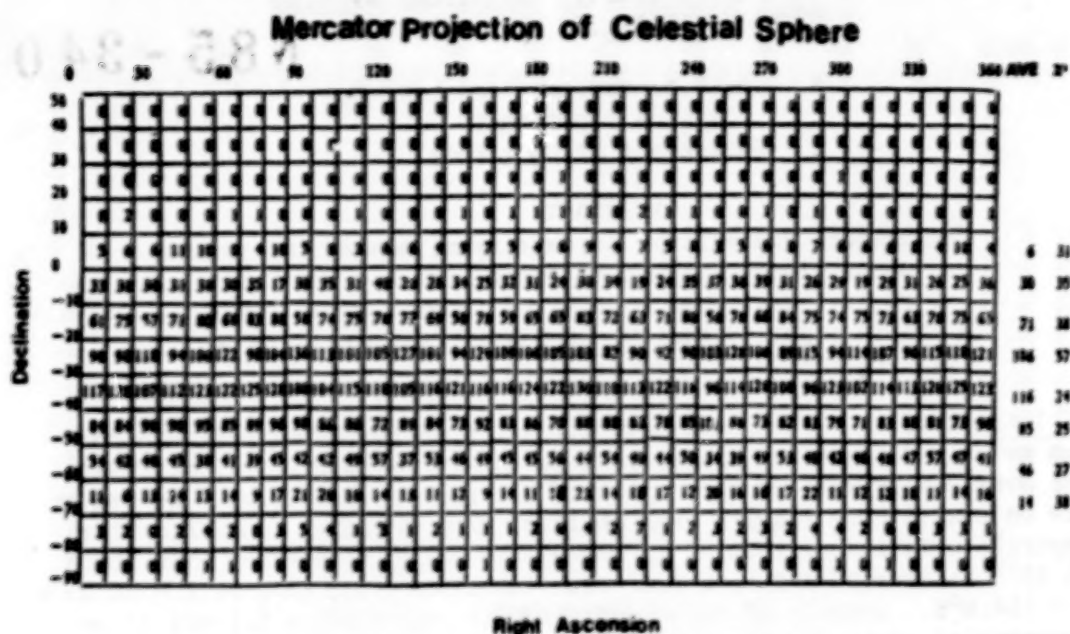
Fig. 3 Cellular division of Mercator Projection of
celestial sphere for 17164 showers.

bands is 12%. Thus the chi-squared tests show no significant evidence
of anisotropy in the tabulated distributions.

4. Acknowlegement

The auther wishes to thank Prof. H. Messel, Prof. C. B. A.
McCusker, Prof. M. M. Winn and Dr. J. Ulrichs in Sydney University
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OG 5.3-9

COSMIC RAY INTENSITY VARIATIONS AT
PRIMARY RIGIDITIES NEAR 1900 GV

N85-34075

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ABSTRACT
Preliminary analysis of an experiment monitoring cosmic
ray muons yields a first sidereal harmonic amplitude
for rigidities around 1900 GV of $(7.95\pm3.97)10^{-4}$ at
5.1 ± 1.9h right ascension. A significant anti-sidereal
first harmonic is, however, also seen.

1. Introduction   Over the past ten years or so steady progress has
been made in determining the anisotropy of arrival directions of cosmic
rays over a very wide energy region of the primary particles. We report
here on preliminary results from an experiment designed to monitor the
temporal variation of cosmic ray muons with energies greater than about
1.6×10^{11} eV carried out in a road side tunnel in Hong Kong at $\lambda = 22.23^{O}$N,
$\phi_E = 114.6^{O}$E. Details of the experiment are reported in [1] and in an
accompanying paper at this conference (Lee and Ng , HE 4.5-15).

2. Basic Data of the Experiment   The telescope, composed of
individually monitored cylindrical proportional counters, is situated
under a rock burden of varying thickness with an intensity weighted
average depth of 573 hg cm^{-2}. This corresponds to a mean muon
threshold energy of 157 GeV. Using a factor of 12.2 to relate the muon
threshold to primary rigidity [2], [3] we have a value for the median
rigidity, $R_{med} = 1915$ GV.

The present report is based on observations made in the period
November 1983 - March 1985, during which time the duty cycle was 80%.
No selection, or cuts, have been imposed at this stage on the data,
which totals 1.27×10^7 counts - an average count rate of 1280 $hour^{-1}$. A
small systematic decrease in the count rate is observed, with an average
fractional rate of change equal to $(-1.6\pm0.6)10^{-5}$. This would contri-
bute to a first harmonic, (at 6 h), a fractional amplitude of 0.32×10^{-4},
much smaller than the formal standard deviation, $\sqrt{2/N} = 4 \times 10^{-4}$, dictated
by the statistics of observation.

3. Harmonic Analysis   An analysis of the data to extract first and
second harmonics at solar, sidereal and antisidereal frequencies has
been performed. Only data from uninterrupted solar days of operation
were included. This was analysed, month by month, by binning it into
12 cell phase histograms. For sidereal and antisidereal frequencies
the phase corresponding to the centre of the bi-hourly solar cell was
used in determining a, weighted, mean phase for each cell of the
composite histogram, with suitable correction to equalise exposure time
for each such cell also being applied. Using fractional deviations of
a cell from the overall cell mean for the month as variable the first
and second harmonics for the three cases were calculated, (in the case
of the sidereal and antisidereal histograms using a trapezoidal rule
integration because the mean phases of the cells in these cases, in

general, are not equidistant). The mean square deviation (variance) of the cell rate, averaged over the 16 months was 14% larger than the Poissonian expectation.

The harmonic amplitudes r, and phase of maximum ϕ, are shown in the table. The formal standard deviation on the amplitudes is

	amp. x 10^4	phase/h	k_0	amp. x 10^4	phase/h	k_0
Solar	1.19	19.0	0.05	7.60	0.1±2.0	1.77
Sidereal	7.95	5.1±1.9	2.62	6.14	4.4±2.5	1.20
Anti-Sidereal	9.57	11.7±1.6	2.91	1.63	0.0	0.08

$\sigma_r = \sqrt{\frac{2}{N}} = 3.97 \ 10^{-4}$, while for the phases $\sigma_\phi = \sigma_r/r$ is shown for those amplitudes which are significant. Also shown in the table is the parameter $k_0 \equiv r^2 N/4$, which determines the significance of these dispersions [4]. From the presentation of the data on harmonic dials, fig.1, it is clear that both the sidereal and antisidereal first harmonic amplitudes are formally significant. The unwelcome appearance
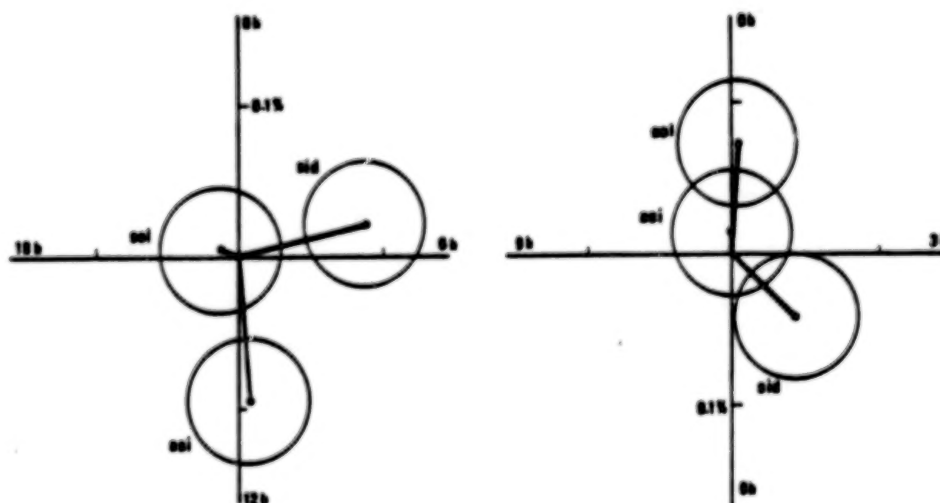
Fig.1 The first and second harmonics at solar, sidereal and anti-sidereal frequencies and their standard deviations

of the latter we have not so far succeeded in explaining. It does not seem that meteorological factors, not yet incorporated in the analysis, can account for such a large effect. Straightforward regression of the observed counting rates on the sea-level pressure, and the atmospheric temperature at the 200 mbar level yield coefficients $-0.04\pm0.02\%$ mbar^{-1} and $+0.12\pm0.07\%$ K^{-1} respectively. Further investigation is in progress to understand this aspect.

4. **Results on Sidereal Harmonics**   Allowing for the non-Gaussian distribution and bias in the mean [4], the expectation values for two sidereal amplitudes, their 95% and 5% confidence levels, their phase of maximum and its 68.3% confidence level are:

$$\xi_1 = 7.95(1.50, 14.71)10^{-4} \qquad \phi_1 = 5.1\pm2.1 \text{ h},$$

$$\xi_2 = 5.28(0.0, 11.7)10^{-4} \qquad \phi_2 = 4.4\pm3.6 \text{ h}.$$
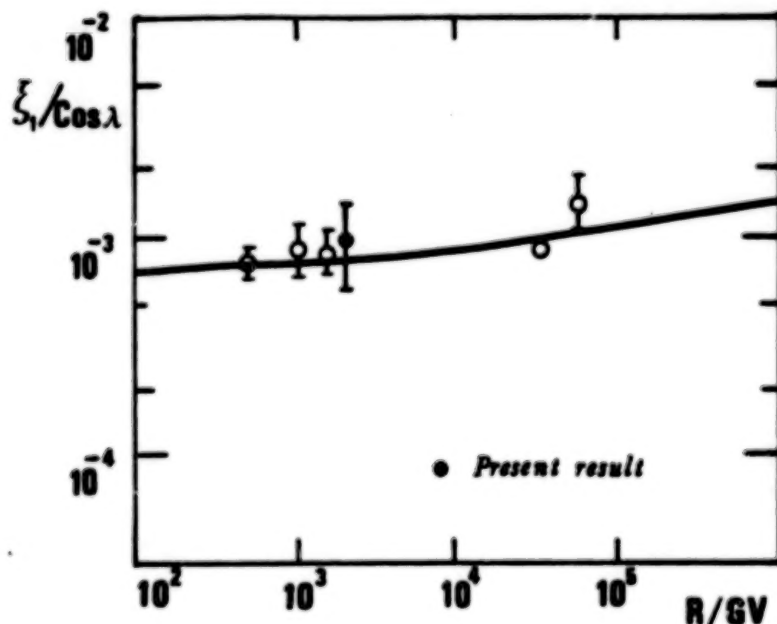
Fig.2 The projected first sidereal harmonic, corrected for solar motion, as a function of rigidity; the curve is due to Tan, paper OG 5.4-13 at this conference.

Although barely significant, especially in view of the unexplained anti-sidereal amplitude noted earlier, both these values are of similar magnitude to those found by other workers in similar regions of rigidity. A correction for solar motion relative to the local interstellar medium, following the parameters used in [2], when applied to the first harmonic amplitude leads to a value $\xi_1/\text{Cos}\lambda = 9.86 \ 10^{-4}$ at $\phi = 4.80\pm2.1$ h. This projected amplitude along with its formal standard deviation is shown in fig.2. Also shown there are the values of other workers as corrected in [2], along with a prediction by Tan, based on his non-uniform galactic disc model for cosmic ray propagation (paper OG 5.4-13 at this conference), corresponding to his

parameter ℓ_s = 5 kpc.

5. Acknowledgements   We are grateful to the Commissioner of Transport, Hong Kong Government for facilities provided in the Aberdeen Tunnel, the Director of the Hong Kong Royal Observatory for the supply of meteorological data, and to the Director of Computer Services, H.K. University Centre of Computer Studies and Applications for the provision of Computer facilities.

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N85-34076

Search for Bursts in Air Shower Data

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1. Introduction   There have been reports in recent years of the possible observation of bursts in air shower data (e.g. Smith et al 1983, Fegan et al 1983). If such events are truly of an astrophysical nature then they represent an important new class of phenomenon since no other bursts have been observed above the MeV level. The spectra of convential gamma ray bursts are unknown at higher energies but their observed spectra at MeV energies appear generally to exhibit a steepening in the higher MeV range and are thus unlikely to extrapolate to measurable fluxes at air shower energies (see e.g. Clay et al, 1982).   On the other hand, we now know that astrophysical objects are indeed capable of producing ultra high energy gamma rays and we should treat seriously the possibility of a burst acceleration mechanism.

We have looked for deviations from randomness in the arrival times of air showers above ~ 10^{14} eV with a number of systems and results so far are presented here. This work will be continued for a substantial period of time with a system capable of recording bursts with multiple events down to a spacing of 4 µs . Following the suggestion of Fegan et al (1983) that their event may be related to a glitch of the Crab pulsar, we have also searched our earlier data for the possible association of air shower events with a glitch of the Vela pulsar.

2. Detecting Systems   Four detecting systems were used in this work. Data from the earlier Buckland Park array was used to search for bursts from the direction of the Vela pulsar. This system has been described in detail elsewhere (Crouch et al [1981]). Data from the new Buckland Park array with a substantially lower energy threshold has been searched for evidence of any non-random component. This array is described in this conference (Clay et al 1985a). We have also used two simple air shower triggers employing, in each case, two scintillators in coincidence. One detector pair was operated at Adelaide with a 5.6m spacing (detector area 0.16 m^2) and a median detected shower size of $Ne = 4 \times 10^4$ particles. The second system, operated at Perth, consisted of two scintillators (area .07 m^2) with a spacing of 6m giving a median shower size of 3×10^4 particles.

3. Searches for any Non-Random Effect   We have previously searched for non-random effects in our air shower time spacing distribution by testing our spacing distributions to see whether or not the exponential form extended to small time spacings. A non-random effect associated with bursts would be likely to result in an excess of small spacings. Since we have no 'a priori' reason for expecting a particular burst time scale, we have fitted exponentials (see Fig 1) for each data set above a

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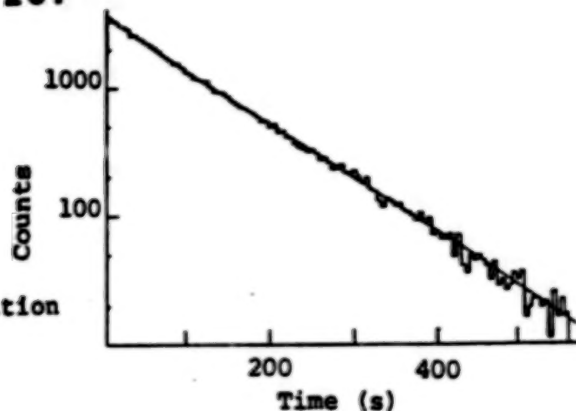
Fig 1. Pulse spacing distribution measured at Adelaide.

lower time spacing limit chosen subjectively by taking into account the recording pulse rate and then compared the number of events expected below this limit with the number actually observed. The results are shown in table 1.

Table 1

Experiment (Recording-Time)	Spacing range for fitted exponential	Mean event spacing	Number exp. below range	Number obs. below range
Buckland Park (964 hrs)	150-1000s	312.6s	4193±63	4192
Adelaide (2139 hrs)	50-1000s	103s	28732±106	28576
Perth (2488 hrs)	400-4000s	977s	3139±43	3183

One might also ask whether or nor there is any evidence for bursts in the data sets in terms of any series of small time intervals rather than an excess in the total number of small time intervals. We have examined our data and calculated for each system the number of times expected for observing a _series_ of 3, 4 or 5 successive intervals, each below a certain minimum spacing. The results are shown in table 2.

Table 2

Experiment	Number of times consecutive time intervals are <t.					
(time-interval t)	3 intervals		4 intervals		5 intervals	
	expected	observed	exp.	obs.	exp.	obs.
Adelaide (20s)	230	221	35.9	44	6.1	8
Buckland Park (2s)	1301	1270	196	245	30	41
Perth (200s)	62.7	71	11.8	10	2.2	2

It is apparent that our data showed no evidence of any non-random effects with a total exposure of 5591 array-hours.

4. Discussion   Previous experiments which have reported the observation of UHE bursts have operated for periods of the order of a year.   That is, long monitoring periods are required.   In order to design an experiment to search for such bursts with the greatest efficiency in terms of data processing effort and use of the available data, it is instructive to examine tables 1 and 2.   Bursts of the type detected by Fegan et al. and Smith et al. would have been detected readily by the technique employed in Table 2 but probably not at all by the method used in Table 1.   A useful way of searching for bursts would then be to minotor any short time intervals between air shower events and to search for any periods which exhibit a series of such short time intervals.   We are now using a time interval measurement device which responds to pairs of events with time spacings below 0.5s (compared to a mean rate of one per 9s with the new Buckland Park array) and records the occurrence of such an event together with the spacing (in units of 4μs).   Bursts can then be identified by the observation of a succession of such short intervals.   This is statistically powerful since the probability of having many successive small intervals by chance falls rapidly with the number of intervals.

5. The Association of Bursts with a Pulsar Glitch   Fegan et al 1983 suggested that their observed burst may have been associated with a pulsar glitch.   The Vela pulsar is at a declination which is easily observed from Adelaide and we have searched our 1979-1981 data set (1.3×10^5 events) for all events within our angular uncertainty arriving from the direction of the Vela pulsar (see Protheroe et al., 1984).   The result of this search is shown in Fig. 2.   These data show no evidence for any clumping.   There is one day which contained three events but such an occurence has a probability of ~66% in a data set of this kind.   The Vela pulsar exhibited a glitch in this time period as indicated but no closely correlated events stand out.

Fig. 2   The day of arrival of events from the direction of the Vela pulsar.   Each column represents 75 days of data.   The time of a glitch is shown as g.
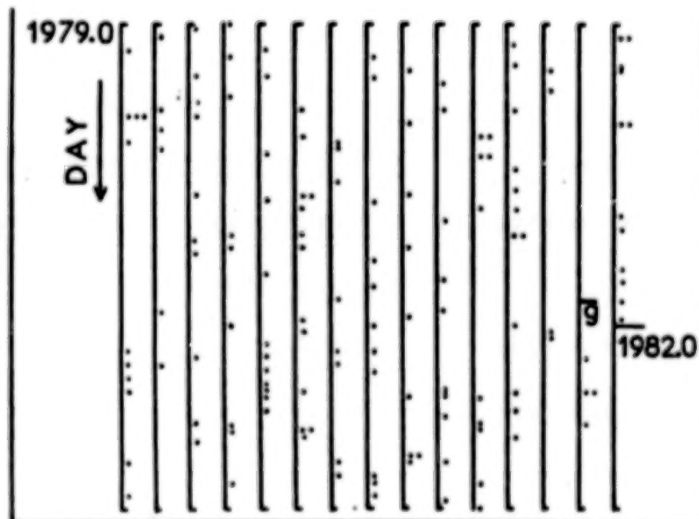
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AIR SHOWER ARRIVAL DIRECTIONS MEASURED AT BUCKLAND PARK

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The Buckland Park air shower array (Crouch et al 1977, Crouch et al 1981) was operated for 3 years from 1979 to 1981 particularly for the study of anisotropies in the region of the knee of the size spectrum. The array which has been described in detail elsewhere was situated at a latitude of 35°S and had an effective size threshold of $\sim 3 \times 10^5$ particles ($\sim 3 \times 10^{15}$ eV for vertical showers). A number of results from this experiment have already been published including anisotropy analyses (Gerhardy and Clay, 1983) and searches for very high energy gamma ray sources (Clay et al. 1984, Protheroe et al. 1984, Protheroe and Clay 1984, Protheroe and Clay 1985). Here we wish to present our final distribution of measured shower arrival directions (Table 1).
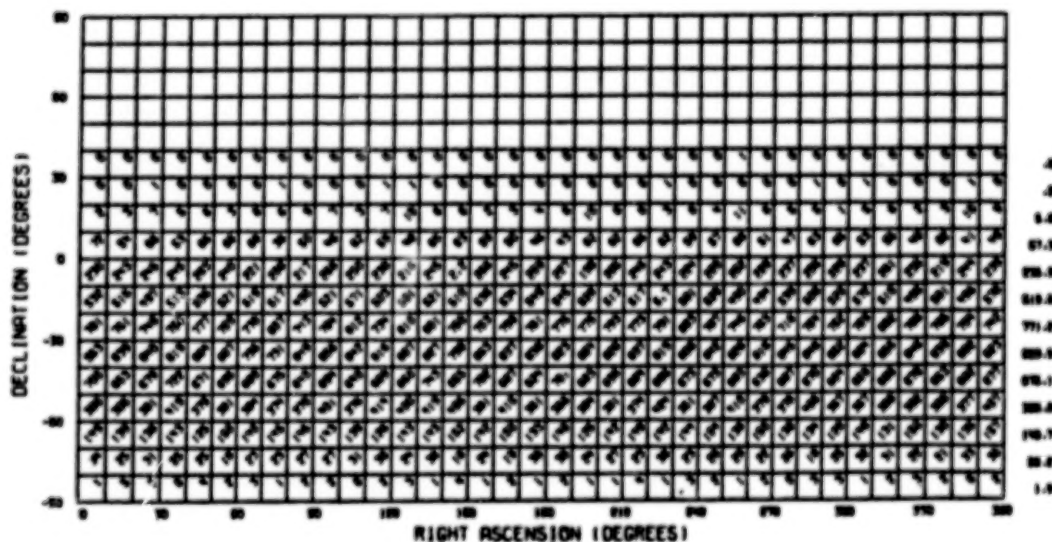
These 1.3×10^5 events were selected as indicated in detail in Gerhardy and Clay (1983) and were essentially those events with well measured arrival directions. They are the same data set used in the above references but no complete sky map has previously been presented.

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A Simulation of High Energy Cosmic Ray Propagation I

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Abstract

We simulate high energy cosmic ray propagation of the energy region $10^{14.5}-10^{18}$ eV in the inter steller circumstances. In conclusion, the diffusion process by turbulent magnetic fields is classified into several region by ratio of the gyro-radius and the scale of turbulence. When the ratio becomes larger then $10^{-0.5}$, the analysis with the assumption of point scattering can be applied with the mean free path E^2. However, when the ratio is smaller than $10^{-0.5}$, we need a more complicated analysis or simulation. Assuming the turbulence scale of magnetic fields of the Galaxy is 10-30pc and the mean magnetic fields strength is 3 micro gauss, the energy of cosmic ray with that gyro-radius is about $10^{16.5}$ eV.

1 Introduction

Many authors have studied cosmic ray propagation in magnetic fields[1]. Especially, Gleeson and Axford had solved a diffusion equation with the assumption that cosmic ray are scattered by scattering centers. The recent observation of Galactic magnetic field[2] shows the average field strength is about 3 micro gauss and the turbulent fields are about 1.5 micro gauss. The gyro-radius of cosmic ray in the energy region, in which we are interested, becomes 0.1-300pc. The random magnetic fields cannot deflect the cosmic rays so hardly, but an amount of small deflection may cause a large scattering angle as a result. We know that, in some cases, we can sum up the effects in terms of point scattering and mean-free-path(mfp). However, we are not sure this is the case in the cosmic ray propagation in the turbulent magnetic fields, especially when the gyro-radius of the cosmic ray becomes near to the scale of irregularities. The assumption of point scattering can be an over simplification in the study of cosmic ray propagation in that energy region. It should be checked by the numerical calculation or simulation.

In this paper, we present a Monte Carlo simulation of cosmic ray propagation in the Galactic space and show a result in terms of diffusion tensor. Gleeson and Axford showed the diffusion tensor have three independent element $(K_{//}, K_{\perp}, K_{T})$. The analytic form of these element as a function of mean free path are given by

$$K_{//} = \frac{1}{3}\lambda c \tag{1}$$

$$K_{\perp} = \frac{K_{//}}{1 + (\omega\frac{\lambda}{c})^2} \quad \text{and} \tag{2}$$

$$K_{T} = \frac{(\omega\frac{\lambda}{c}) K_{//}}{1 + (\omega\frac{\lambda}{c})^2} \tag{3}$$

where λ is the mfp and ω is the gyro frequency of cosmic rays in that magnetic field. When we leave from the idea of point scattering of cosmic

ray, we should not use mfp at the beginning of the study. Rather it should be given as the result of diffusion process. In our simulation, we calculate the two diagonal elements $K_{//}$ and $K_{\perp}$. We check the consistency comparing these formula. When the consistency is maintained, we try to calculate the mfp from the formula.

2 Generation of random magnetic fields

It seems to be a difficulty in the simulation with irregular magnetic fields to make the flux line conserved. This difficulty is avoided in our case by generating the vector potentials by random numbers. The steps to generate the random magnetic fields are following. First we embed a lattice in the simulation space, whose lattice constant is chosen as the scale of the irregularity of the magnetic field. We generate the vector potential $A=(A_x, A_y, A_z)$ for each lattice point with the probability given by

$$\exp(-A_i/t) \; dA_i \quad (i=x,y,z),\qquad (4)$$

where t is a parameter to adjust the irregular magnetic fields strength. The vector potential in the point other than the lattice points are given by linear interpolation. The irregular magnetic fields are given by

$$\overrightarrow{DH} = \mathrm{rot}(\overrightarrow{A}),\qquad (5)$$

with the random vector potential A. The total fields are given as the sum of irregular magnetic field and average field. When we wish to simulate the turbulent magnetic fields with some spectrum like the Kolmogorov's one, we prepare a series of lattices with different lattice constants. And sum up the irregular magnetic fields with the weight given by the spectrum.

The motion of the cosmic ray particles is determined by equation of motion;

$$m \frac{d\overrightarrow{v}}{dt} = q(\overrightarrow{E} + \overrightarrow{v} \times \overrightarrow{H}).\qquad (6)$$

However, in our simulation we neglect the effects from $\overrightarrow{E}$. In other words, we assumed the magnetic fields is statical. This assumption can be justified because the velocity of cosmic ray is essentially light velocity, but the velocity of the magneto-hydrodynamical waves are around 10^{-3} times of light velocity in the interstellar circumstances. This also means that in our simulation, we neglect the effect of Fermi type acceleration or the diffusion process in energy axis.

3 Simulation

Our simulation is carried out as follows. We assumed that the average magnetic field(H_0) is aline with z-axis, and the average strength of the magnetic field is 3 micro gauss and that of the turbulent magnetic fields are 1.5 micro gauss in average. (We note that what is really meaningful is the ratio $\langle DH \rangle / H_0$, which is 1/2 in our case. The absolute strength is needed when we translate the gyro-radius to the energy in the relation to the scale of the turbulence in relation to the (maximum) turbulent scale $(=L_0)$). We first put a number of cosmic ray particles at the origin and follow the motion numerically determined by the equation. The step time for solving (6) numerically is chosen as 1/10 of the gyro frequency and is changed with gyro frequency. This step time is chosen so that the error caused by it is small in our numerical calculation and that the simulation is executed within the reasonable cpu-time. Taking the statistics of the position of cosmic ray in terms of $\sigma_{\perp} = \sqrt{\langle x^2 + y^2 \rangle}$ and $\sigma_{//} = \sqrt{\langle z^2 \rangle}$, we can calculate

$K_\perp$ from the time dependence of $\sigma_\perp$ and $K_{//}$ from the time dependence of $\sigma_{//}$. The random magnetic field is regenerated every 250 step to accelerate the conversion of diffusion constants to average value.

4 Results

In fig.1, we show a result of our simulation in the form of dimension-less quantity; $K_i/(c \times L_0)$, where i stands for // and $\perp$, c right velocity and L_0 for maximum turbulent scale. The simulation of fig.1 is carried out by assuming that the magnetic fields' turbulence follows the Kolmogorov spectrum. The crosses and close ones show $K_{//}$ and $K_\perp$ respectively. We also made a simulation by assuming of the only one turbulent scale. We found a little difference between them. In both cases, however, we can say that the qualitative tendencies are the same. Therefore the farther simulation is executed assuming the only one scale in turbulence of magnetic field.

Fig. 1

The whole region can be divided into several regions by the diffusion tensor dependences on the R_L. When R_L is in the region between $10^{-1.5} \times L_0$ and $10^{-0.5} \times L_0$, the ratio $K_{//}/K_\perp$ is almost constant and both are proportional to $R_L^{0.3-0.4}$. When R_L becomes lager than $10^{-0.5} \times L_0$, $K_{//}$ is proportional to R_L^2 and $K_\perp$ is almost constant. We also gave a scale in fig.1 to read the mfp directly from $K_{//}$ using (1). We find in the region where the R_L is larger than $10^{-0.5} \times L_0$, (2) gives consistent relation between $K_\perp$ and $K_{//}$ assuming the mfp. However, the relation (2) is not fold for R_L smaller than $10^{-0.5} \times L_0$. We may see that there is an another region, where the radius is smaller than $10^{-1.5} \times L_0$, the slope of $K_{//}$ dependences on the R_L changes to steeper($\sim R_L$). However, the ambiguity of the calculation becomes large in this region and the reliability of simulation may be small.

We also executed simulations with the condition $\langle DH \rangle/H_0 = 1$ and $1/4$ assuming of the only one (maximum) turbulent scale. These results are shown in fig.2 and in fig.3. The simbols are same with fig.1. The whole region is divided into three regions at the R_L; $10^{-1.5} \times L_0$ and $10^{-0.5} \times L_0$. The dependences of $K_{//}$ and $K_\perp$ on R_L are the same with the case of $\langle DH \rangle/H_0 = 1/2$. However, there is a quantitative difference in the value of $K_{//}$, $K_\perp$ and in the ratio $K_{//}/K_\perp$. They are rather rapidly varying functions of the $\langle DH \rangle$.

5 Summary and Discussions

If we assume that the turbulent scale(L_0) is 30pc and the average magnetic field strength is 3 micro-gauss, the energy of the cosmic ray with the gyro-radius $10^{-0.5} \times L_0$ is $10^{16.5}$ eV for the protons. For the higher energy cosmic rays, the assumption of point scattering in the study of its propagation in Galactic space is a fairly good approximation with the mfp $\sim E^2$. However the facter in front of the power of E is a rapidly varying

Fig. 2

Fig. 3
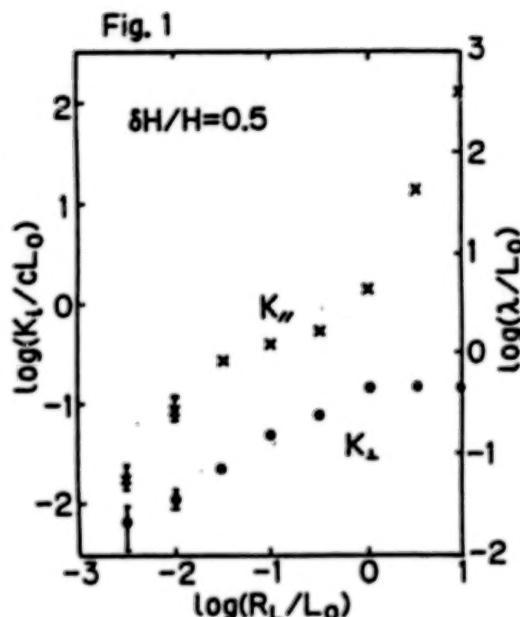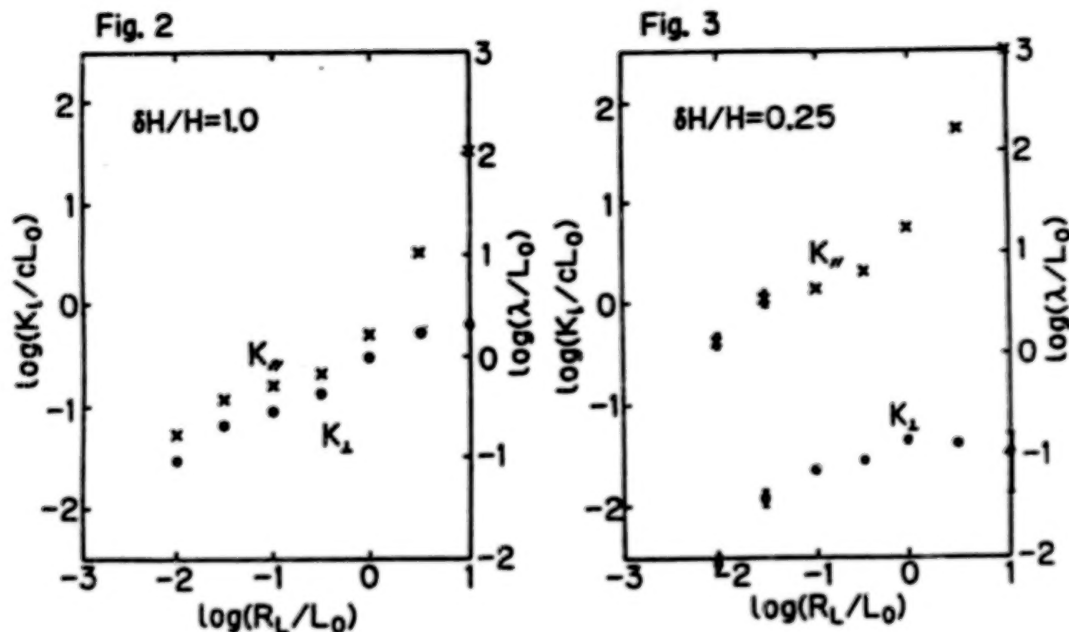
function of $\langle DH \rangle$. We note, however, that this is a result of the accumulation of small deflection by the magnetic fields and the facter should be obtained by different method; for example simulation. For the lower energy cosmic rays than $10^{16.5}$ eV, the diffusion constants do not follow the formula (1)-(3). To study the cosmic ray propagation in this region, we need a simulation or more sophisticated analytic methods. It is noted that in this region the ratio of $K_{//}$ and $K_{\perp}$ is almost constant. If we assume the average strength of turbulent magnetic field is 1.5 micro gauss, the ratio is about 10. For the smaller energy cosmic ray than $10^{15.5}$ eV, the result of the simulation show a relatively large difference between different random number series. This fact might indicate that the other mechanism than the diffusion process like convectionshold be considred in the study of the propagation of cosmic ray with this energy in the Galaxy.

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A Simulation of High Energy Cosmic Ray Propagation II

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Abstract
       The cosmic ray propagation in the Galactic arm is simulated. The
Galactic magnetic fields are known to go along with so called Galactic arms
as a main structure with turbulences of the scale about 30pc. We study the
distribution of cosmic ray in Galactic arm and discuss the escape time and
the possible anisotropies caused by the arm structure.

1 Introduction

       In the previous paper[1], we have reported a method to simulate the
propagation of the cosmic ray in the turbulent magnetic fields. (We refer
that paper as I here after). In this paper, we make a little extension of
the work in I. The magnetic field in Galaxy is now considered to be alined
along the Galactic arm. We simulate the propagation of the cosmic ray in the
Galactic arm. It is expected that the cosmic ray is trapped in magnetic
field of arm just like in TOKAMAK. We are interested in the distributions of
cosmic rays in the Galactic arm by following reasons. As the origin of
anisotropy of the arrival direction of cosmic ray, one may consider two
reasons; the source distribution and the propagation in the Galaxy
(including the leakage from it). If the distribution of the cosmic ray is
not uniform, we can expect the anisotropy from the latter reason. As many
authors suggested, the main reason of the acceleration of cosmic ray is by
the shock waves from the supernova[2], the both reasons for anisotropy can
be considered as the same thing. The study of the distribution of cosmic ray
becomes important. We will study the possible anisotropy caused by the arm
structure (or by the distribution of cosmic ray in the arm) and the escape
of cosmic ray from the Galactic arm.

2 Magnetic field in Galactic Arm and Model

       The method of Rotation Measure as well as others[3-4] gave us the
informations of the Galactic magnetic fields. It can be summarized as
follows; the main structure of magnetic fields is aline along the Galactic
arms and its average strength is 3.0 micro gauss. About the turbulence of
magnetic fields, the strength is about 1.5 micro gauss and the scale of the
turbulences is 10-30pc in average.

       As a model of the Galactic arm, we consider a right cylinder with the
radius of 300pc, which is comparable to the thickness of Galactic disc
determined by the rotation measure. We identify the axis of the cylinder
with the z-axis. The 'average' magnetic field is assumed to be alined along
the cylinder axis. The magnetic field is assumed as the sum of 'average' one
and the turbulent ones. The 'average' magnetic fields varies with radius by

$$H(r) = H_0 x \, \exp(-r^2/r_0^2) \quad , \qquad (1)$$

where r_0 is taken to be the radius of galactic arm; 300pc. H_0 is determined so that the average of the magnetic field inside the arm is 3 micro gauss. (The average of turbulent magnetic fields is 0.) The generation of turbulent magnetic fields is essentially same with I. However, the strength of the turbulent magnetic fields with same r is generated proportional to 'average' magnetic field in average. The scale of magnetic fields' turbulence are taken 30pc.

3 Simulation

The simulation is executed almost same way with I. However, in this case the initial distribution of cosmic ray is taken as the uniform distribution in the Galactic arm. The directions of velocity are assume uniform. When a cosmic ray goes beyond r_1 from the arm axis, it is considered to escape from the arm. In this simulation r_1 is taken 600pc, with which distance, the gyro radius in the magnetic field given by (1) is comparable to or larger than r_1 for protons with energy greater than $10^{16.5}$ eV. (In this paper, we assume implicitly that the cosmic rays are <u>protons</u>.) We observe the distribution of cosmic rays and calculate the escape probability of cosmic ray from the arm. To save the cpu time, we made a trick that the escaped particles are resumed into the arm with the position determined by the probability proportional to the distribution of other cosmic rays. This resumption is executed for the every time step corresponding to 250 years. With this trick the number of cosmic rays in simulation is kept constant. The escape probability is calculated from the resumed particle number after the distribution of cosmic ray is considered stational for a few 10^4 years. The step time for the calculation of cosmic ray particle motion is taken 1 year for 10^{16} eV and $10^{16.5}$ eV and 10 years for greater energy than 10^{17} eV. The step time is same or smaller than that of I.

4 Result
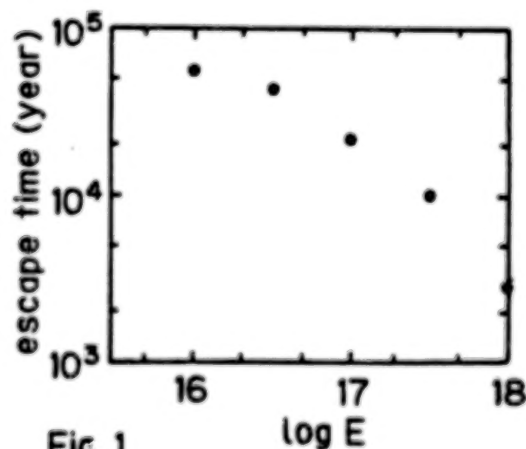
Fig. 1

In fig.1, we show the escape time calculated by the escape probability. It is interesting that the escape time for the cosmic ray with energy $10^{16-16.5}$ eV is consistent with the extrapolation of the life time of lower energy by $E^{-(0.3-0.4)}$. The slope of the escape time larger than $10^{17.5}$ becomes steeper, which can be considered as the reflection of the structure of the Galactic arm. We note the escape time of the energy 10^{16} eV may show a smaller value, because the r_1 used in this simulation is too small to consider that the cosmic ray at r_1 surely escape from the arm. They can be return into the arm with the gyro motion by the magnetic field. In the region $10^{16.5-17.5}$ eV, the escape time is proportional to $E^{-(0.5-0.6)}$.

In fig.2, we show the r-distributions of the cosmic ray for various energy after 10^5 years when the distribution of cosmic ray is considered already stational. The r-distribution of cosmic ray with the energy lower than $10^{17.5}$ eV show a similar feature. In this energy region the cosmic ray density decrease exponentially. We can consider that the cosmic rays are trapped in the Galactic arm. The r-distribution with the energy 10^{18} eV show

a large difference from the lower
one, which shows a slower decrease
with r. This distribution suggests
that the cosmic ray is not trapped
in the arm so long time and easily
escape from the arm. This is also
shown in the escape time of this
energy. It also noted that the
distribution of cosmic ray with the
energy 10^{16}eV is different from the
$10^{16.5-17.5}$eV in the shape of the
slope. This may indicate the
distribution of cosmic ray with
that energy is still in the course
of the formation of stational form
within the simulation corresponding
to 10^5 years. After the formation
of the stational form, the escape
probability can be smaller.

In fig.3, we show the V_θ in
average over all cosmic rays for
various energies. V_θ is defined by;

$$V_\theta = \frac{X \cdot V_y - Y \cdot V_x}{\sqrt{X^2 + Y^2}} \qquad (2)$$

We can see the V_θ become
considerably large for larger energy
than $10^{16.5}$eV. It takes its maximum
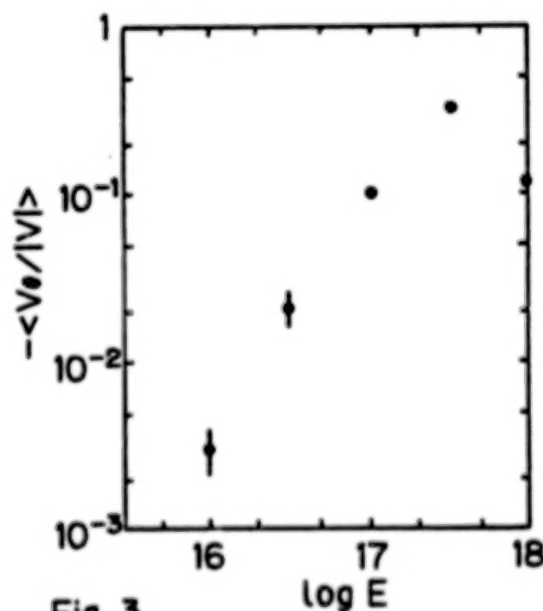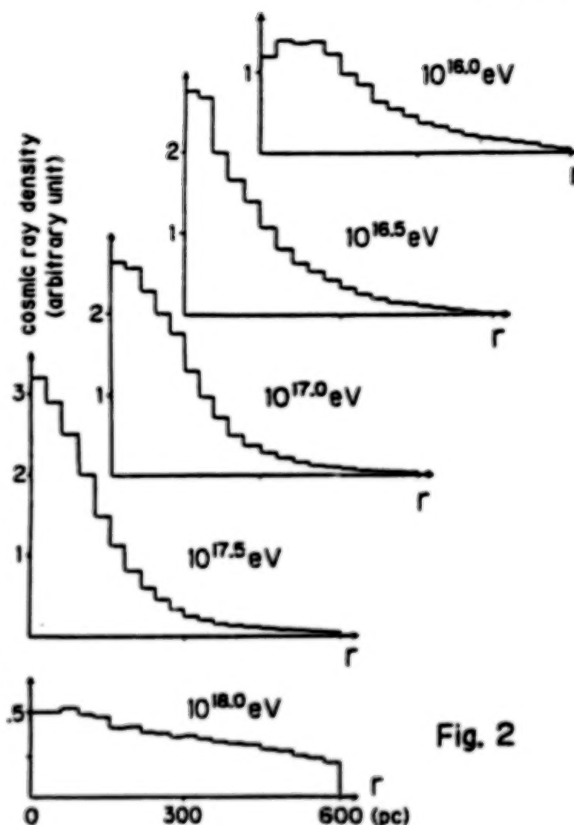
Fig. 2

at $10^{17.5}$ and in the energy 10^{18}eV it
becomes smaller value. This value have
direct relation to the anisotropy of
the arrival direction of cosmic rays.
In the energy $10^{16.5}$eV, we can expect a
few % of excess of the number of cosmic
rays coming from the rotational
direction around the arm axis and in
the energy $10^{17.5}$eV a few 10%. In the
energy of 10^{16}eV, this value also show
a non-zero V_θ value. However, this
value fluctuates with time and also
varies with r. We are not sure the we
can expect the anisotropy in this
energy.

In fig.4 we show the average of
$|V_z/V|$ in various energies. If the
direction of cosmic ray velocity is
isotropic, this value is 0.5. In the
energy 10^{18}eV, it shows a large
deviation from 0.5 to a larger value:
0.6. The direction of velocity of
cosmic rays, which stay in the arm for
long time, are not uniform in this
energy. In the lower energy, the value

Fig. 3
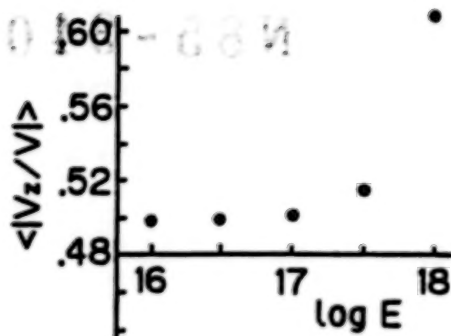
is very near to 0.5. In the context of anisotropy, $|V_z/V| > 0.5$ means there is an excess in the numbers of cosmic rays coming from the direction parallel to the arm axis. In this case the anisotropy is observed as the second harmonics.

Fig, 4

5 Summary and Discussions

We have shown that the cosmic rays with the energy lower than 10^{18} eV are trapped in the Galactic arm. As the physical consequences, we can expect a few % (first harmonics) anisotropy of the arrival direction of cosmic rays in the energy region $10^{16.5-17.5}$ eV to the rotational direction around the arm axis. We note this is the direct consequence of the distribution of cosmic ray and the gyro-rotation of them in the magnetic field. In the energy 10^{18} eV, the cosmic ray become easy to escape from the Galactic arm. The cosmic ray, which stay long time in the arm have smaller pitch angles. Therefore we can expect the anisotropy of second harmonics to the direction of arm axis. (Of course, if there is typical source near to the Earth, the anisotropy in this energy region is affected by it.) For the lower energy than 10^{16} eV, the effect of arm structure in anisotropy of the arrival direction is uncertain. The anisotropy observed in this energy may be the reflection of the local structure of the Galactic magnetic field. It should be noted the magnitude of the anisotropy predicted here is consistent with the observations[5]. However, the direction determined by the observation is different from our result. The observation of the anisotropy in the energy region above $10^{16.0}$ eV have some ambiguity yet caused by poor statistics. The more elaborate experiments are expected.

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COSMIC RAYS IN THE 10^{16} TO 10^{19} eV RANGE FROM PULSARS

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Abstract. We calculate the flux of cosmic rays (CRs) produced by a distribution of pulsars that are (1) born with rapid rotation rates, (2) slowdown as they evolve, and (3) produce energetic nuclei with a characteristic energy proportional to their rotation rates. We find that, for energy independent escape from the disk of the galaxy, the predicted spectrum will be essentially what is observed between ~ 10^{16} to 10^{19} eV if the slowdown law as inferred for radio pulsars can be extrapolated to young pulsars with shorter periods.

1. Introduction. The recent discovery of ultra-high energy γ-rays from compact sources such as Cygnus X-3 (Samorski and Stamm 1983) has renewed speculation that compact objects may produce a significant fraction of the observed galactic CRs (Hillas 1984b; Chanmugam and Brecher 1985). Almost immediately upon the discovery of pulsars, they were suggested as possible sources of CRs (e.g. Ostriker and Gunn 1969). However, two major problems led most researchers to discount pulsars as important contributors to the CR flux. The first is the highly unlikely possibility that pulsars can produce nuclei in the GeV range with the observed CR composition. The observed composition at these energies is essentially the same as universal abundances (e.g. Meyer 1985) and strongly argues against sources as exotic as pulsars.

The second problem concerns the ability of pulsars to produce ultra-high energy nuclei. Pulsars store vast amounts of energy in their rotational motion, and their large surface magnetic fields combined with rapid rotation imply vacuum potentials in the CR energy range. However, it was considered doubtful that pulsars could produce nuclei with energies even remotely approaching the limit of their vacuum potentials (e.g. Arons 1981).

Recent developments have prompted us to reexamine pulsars as possible CR sources. First, a relatively self-consistent explanation for CRs below ~ 10^{15} eV has been developed (e.g. Axford 1981). In this model, expanding supernova blast waves accelerate CRs out of the ambient interstellar medium. While many important details remain to be clarified, supernovae, combined with first-order Fermi shock acceleration, can be expected to account for the observed CR energy spectrum, energy budget, and composition up to ~ 10^{15} eV. Above this energy, however, it becomes highly unlikely that supernova shocks can accelerate particles (Lagage and Cesarsky 1983; Wandel 1985; for an alternative view, see Jokipii and Morfill 1985). A feature in the CR spectrum is seen near 10^{15} eV and the spectrum steepens above ~ 10^{16} eV, suggesting that these CRs may have a distinct origin. From ~ 10^{16} to 10^{19} eV the observed CR spectrum is well described by a power law with index -3 (e.g. Hillas 1984a). Measurements of the composition become very difficult at these energies and few constraints on CR composition exist above ~ 10^{16} eV.

Second, Michel and Dessler (1981) have proposed that active radio pulsars may be surrounded by fossil disks left over from the collapse that produced the neutron star. In this model, the neutron star and disk act essentially as two coupled unipolar generators and are capable of

maintaining potential differences of the order of the vacuum potential, i.e., $\sim a^2 B\Omega$, where a is the radius, Ω is the angular velocity, and B is the surface magnetic field of the pulsar. These authors suggest that nuclei can be accelerated from the disk (having near solar abundance) to energies on the order of this potential.

We also note that γ-rays with energies in excess of 10^{16} eV have been observed from Cgynus X-3 (Samorski and Stamm 1983). This is reasonably clear proof that compact objects can accelerate nuclei to CR energies regardless of our inability to understand how they do it.

In light of this, we examine a simple model for the production of CRs by a galactic distribution of pulsars. These pulsars would be born with high magnetic fields and millisecond (ms) periods, and would evolve according to the slowdown relation, $d\Omega/dt \propto \Omega^n$, where n is the braking parameter. The range in radio pulsar periods implies that this source would cutoff below $\sim 10^{16}$ eV and produce CRs rays up to $\sim 10^{19}$ eV, where another feature in the spectrum is observed. Cosmic rays above $\sim 10^{19}$ eV would be produced by yet another source that is most likely extra-galactic (Hilles 1984a).

2. **Model.** We assume that pulsars are born at the rate, $Q(\omega)$. Their evolution may be described by a diffusion equation in Ω space:

$$\frac{d}{d\Omega} (N \, \dot{\Omega}) = Q(\Omega), \tag{1}$$

where $\dot{\Omega} = d\Omega/dt$ and $N(\Omega)d\Omega$ is the number of pulsars per unit volume in $d\Omega$. For simplicity we assume that all pulsars are born with the same Ω_{max}, i.e., $Q(\Omega) = Q_0 \delta(\Omega-\Omega_{max})$. Equation (1) can then be solved to give

$$N = - Q_0/\dot{\Omega}. \tag{2}$$

Now, on very general terms, the magnetic torque should slow the pulsar so that

$$\dot{\Omega} \propto \Omega^n, \quad \text{with } n = 3. \tag{3}$$

This result, which is essentially a dimensional consideration and is quite model independent, is also backed by observations of radio pulsars (for a detailed discussion see Michel 1982).

Next we assume that pulsars produce nuclei with energies comparable to the vacuum potential, i.e.,

$$E_{vp} \sim \frac{e}{c} a^2 B\Omega \sim 6 \times 10^{19} \left(\frac{a}{10 \text{ km}}\right)^2 \left(\frac{10^{-3} s}{P}\right) \left(\frac{B}{10^{12} \text{ G}}\right) \text{ eV}, \tag{4}$$

where P is the pulsar period in seconds.

The particle spectrum produced by a distribution of pulsars, each having a differential flux, $f_\Omega(E)$, is given by

$$F(E) = \int N(\Omega) f_\Omega(E) d\Omega. \tag{5}$$

If the particle spectrum of a specific pulsar is peaked at its vacuum potential, i.e., $f_\Omega(E) = \delta[E-E_{vp}(\omega)]$, eqs. (2)-(5) can be solved to yield

$$F(E) \propto E^{-n}, \quad 10^{16} \lesssim E \lesssim 6 \times 10^{19} \text{ eV}, \tag{6}$$

where we have assumed that the flux of particles emitted by a pulsar is independent of Ω. The energy range is determined by a spread in pulsar periods from ~ 1 ms to 4 s. If n = 3, this is just the observed slope of the CR spectrum in the above energy range.

The above solution can be shown to be independent of the spectrum emitted by an individual pulsar. For an emitted spectrum of the form

$$f_\Omega(E) \propto \Omega^q E^\alpha, \tag{7}$$

we find that $F(E) \propto E^{-n+q}$ and is essentially independent of α if $\alpha > -1$ (Wandel and Ellison 1985).

3. Discussion It is remarkable that a straightforward application of zeroth-order pulsar theory yields a spectrum consistent with the observed CR spectrum above ~ 10^{16} eV. There are, however, many complicating factors that may alter this result. (a) Pulsars may be born with a distribution of periods, or with periods considerably longer than 1 ms. We note that the ms pulsars that have been observed to date may have been spun-up, have low magnetic fields, and would not produce the energetic particles we envision. A recent survey at 1.4 GHz (Manchester et al. 1985) suggests, however, that many short-period pulsars would be discovered by searches with improved sensitivity. (b) Pulsars may not produce nuclei at energies near the vacuum potential. Cygnus X-3 produces highly energetic nuclei, but is not of the class of objects considered here. (c) Instead of a delta function at E_{vp} as we have assumed, an individual pulsar may produce particles with a distribution of energies. However, due to the rapid pulsar evolution, the distribution of CRs produced by a population of pulsars is insensitive to the shape of the spectrum from a single pulsar, as discussed above. (d) We assume that the particle flux produced by an individual pulsar is independent of Ω [i.e. $|q| \ll 1$ in eq. (7)]. The flux is determined by the details of the pulsar model and may depend on the geometry and magnetic field, which are assumed to vary slowly. Note, however, that if the emitted particle flux is related to the rotational energy loss, $dE/dt = I\Omega\dot{\Omega}$ (I = moment of inertia), the flux would be expected to be a strong function of Ω. (e) The braking parameter may not be constant and equal to 3. For instance, if the neutron star has a finite quadrupole moment (e.g. due to an internal field or a secular rotational instability), gravitational radiation would be emitted. If the neutron star looses angular momentum mainly due to gravitational radiation, then n ~ 5. For parameters typical of the Crab pulsar (Ostriker and Gunn 1969; Alper and Pines 1985), gravitational quadrupole radiation dominates magnetic dipole radiation only for P < 1-2 ms, so that the relevant Ω range is not affected significantly. (f) We must consider the effect of propagation on the source spectrum, eq. (6). This is treated below.

At energies below ~ 10^{15} eV, the interpretation of the secondary to primary nuclei ratios implies that the CR source spectrum is significantly steepened by propagation and energy dependent escape from the galaxy (e.g. Protheros et al. 1981). At the energies considered here, however, there is no direct evidence that the source spectrum is modified by propagation. On the contrary, if we extrapolate the inferred scattering mean free path, λ_s, from lower energies (Ormes 1983) to 10^{16} eV, we find it is (for protons) of the order of the scale height of the galactic disk, and increases for higher energies. This suggests that

the diffusion approximation is not justified at energies above 10^{16} eV. If these high energy particles are not confined, the observed CR spectrum is not modified by an energy-dependent leakage term, as it is at lower energies, hence the slope of the observed spectrum will be the same as the source spectrum.

The observed CR flux above $\sim 10^{16}$ eV requires $\sim 4 \times 10^{50}/t_r$ erg/s, where t_r is the CR residence time in the disk and we have assumed a typical disk volume (e.g. Hillas 1984b). For scatter free propagation, $t_r \sim 10^{3.5}$ yr. However, the mean free path at $\sim 10^{16}$ eV may be smaller than the scale height of the disk (e.g. if heavy nuclei contribute), in which case t_r would be significantly larger (e.g. if $\lambda_s \sim 50$ pc, $t_r \sim 10^5$ yr). The energy required to power the observed CR spectrum above $\sim 10^{16}$ eV would, in that case, be $\sim 10^{38}$ erg/s (cf. Hillas 1984b). This is only a fraction of the rotational energy loss of the Crab pulsar ($I\Omega\dot\Omega \sim 5 \times 10^{38}$ erg/s). At higher energies, the residence time in the disk decreases to the scatter free value, but on the other hand, the energy required to power CRs decreases as $1/E$ while the energy input available from pulsars is $\propto NI\Omega\dot\Omega \propto E$. The rotational energy in pulsars is, therefore, more than sufficient to power CRs above 10^{16} eV.

In addition, the increase in anisotropy of CRs which is observed above $\sim 10^{15}$ eV, may also be due to the mean free path becoming comparable to the thickness of the disk. If λ_s is ~ 100 times the gyroradius, the transition energy should be in the range of 10^{15} to 10^{16} eV as observed.

4. Conclusions. We have found that the observed cosmic ray spectrum in the energy range, $\sim 10^{16}$ to 10^{19} eV can be produced by a distribution of pulsars if they are born with ms periods, evolve according to $\dot\Omega \propto \Omega^3$, and emit nuclei with energies characteristic of their vacuum potentials. As indicated, this simple model makes several assumptions, some of which are ad hoc. However, we find it remarkable that the proper CR spectrum and energy range are reproduced with minimal assumptions and with virtually with no free parameters. This result is essentially independent of the spectral details of individual pulsars.

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ENERGY DEPENDENCE OF COSMIC RAY COMPOSITION ABOVE 10^5 GEV/NUCLEUS

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ABSTRACT

It is argued that above 10^5 GeV/nucleus, in the range
where charge-resolved spectra have not yet been determined,
the appropriate measures of equal-energy composition are
<lnA> and {lnA}, the mean value and dispersion relative to
the mean of lnA, where A is the mass number. Experimental
data which are sensitive to changes in <lnA> with increas-
ing energy are examined. It is found that, taken as a
whole, they show no change (±0.5) between 10^5 and 10^6 GeV,
and a *decrease* of 1.5 ± 0.5 between 10^6 and 10^8 GeV, with no
further change (±0.5) above 10^8 GeV. Taken as a whole,
the various indirect estimates of the absolute value of
<lnA> above 10^5 GeV/nucleus are also consistent with this
pattern. For a wide range of astrophysically plausible
composition models the value of the other measure, {lnA},
is insensitive to changes in <lnA>. Because of this the
existing data on {lnA} can likewise easily be reconciled
with this pattern.

1. Introduction. The energy spectra of all the elements, insofar as
they have been measured to date at the top of the atmosphere or above
it, are well explained by a simple leaky box model with fragmentation in
the interstellar medium and a rigidity dependent escape length. How-
ever, measurements of charge-resolved spectra are increasingly difficult
at higher energies. Particles are usually selected on the basis of en-
ergy per nucleus, the practical upper limit being at present about 10^5
GeV/nucleus. The composition of cosmic rays with equal energy is
strongly biased in favor of heavy elements compared to cosmic rays with
equal magnetic rigidity. Below 10^5 GeV/nucleus the equal-energy mass
spectrum is in fact nearly rectangular from protons to iron.

Above 10^5 GeV/nucleus the evidence on cosmic ray composition is in-
direct. There is overwhelming evidence that nearly all of these cosmic
rays are bare atomic nuclei, as at lower energies, rather than electrons,
γ-rays, neutrinos, dust grains, or exotic objects such as quark globs,
magnetic monopoles, or mini-black holes. The indirect experiments are
sensitive to primary mass rather than charge, but in view of the low
resolution, conversions from one to the other are carried out assuming
that $Z = A/2$ for nuclei other than protons. With a few exceptions the
indirect methods select primaries of a given energy per nucleus, rather
than energy per nucleon. They are unable at present to resolve the mass
spectrum into individual nuclei or even groups of neighboring mass.
With a few exceptions they can be classified into two groups: those

which measure the average primary mass and those which measure the width of the primary mass distribution. In most cases the theoretical line separation is proportional to lnA rather than A. For this reason, and to avoid giving undue importance to elements in the Fe group, it is preferable to use lnA as the underlying variable, and to group the experiments into some which measure the mean value <lnA> and others which measure {lnA}, the dispersion of lnA relative to the mean. The remainder of this work summarizes the available experimental evidence on the energy dependence of these two quantities, with emphasis, of course, on energies above 10^5 GeV/nucleus.

2. Low Energy Region. The behavior of <lnA> and {lnA} as a function of energy/nucleus is shown in Fig. 1. For energies $\leq 10^5$ GeV the points are calculated from directly observed charge spectra (see Linsley 1983). In this region the value of <lnA> increases from 1.0 at 10^2 GeV to 1.7 at 10^4 GeV and then levels off. Although one cannot rule out a certain degree of heavy enrichment at the sources in the upper part of this range (Juliusson 1975, Goodman *et al.* 1979), it is not necessary to assume any such enrichment; the increase of <lnA> can be explained entirely by a diminished path length at higher energies, resulting in less fragmentation of nuclei such as Fe during propagation from the sources to the earth. There is direct evidence from the JACEE experiment that the value of <lnA> is not significantly greater at 10^5 GeV than at 10^4 GeV (Burnett *et al.* 1983), and there is direct evidence from an experiment by Sood (1983) that the intensity of Fe nuclei at the top of the atmosphere is no greater at 10^5 GeV than predicted by the standard model.

3. High Energy Region. A number of ground level experiments measure <lnA>. Calibration is a problem, so some results are sensitive mainly to *changes in* <lnA> vs E, while others yield estimates of the absolute value of <lnA>. One approach uses data on x_m, the atmospheric depth at which air showers reach maximum development; another uses data on N_μ, the number of muons for a fixed number of electrons at ground level. For a given primary A, barring any sudden unexpected changes in the character of high energy interactions, $<x_m>$ and $<lnN_\mu>$ are expected

Fig. 1. Energy dependence of <lnA> and {lnA}. CLOSED CIRCLES, calculated from charge-resolved spectra obtained in many balloon experiments; CLOSED DIAMONDS, Burnett et al. 1983; CLOSED SQUARE, Linsley & Watson 1981 from $<x_m>$ obtained in several air shower experiments; OPEN CIRCLES, Acharya et al. 1983; OPEN DIAMOND, Nikolskii et al. 1979; TRIANGLE, Hara et al. 1983; INVERTED TRIANGLE, upper limit from $\{x_m\}$ obtained in several air shower experiments; OPEN SQUARE, upper limit from $\{lnN_\mu\}$ (Volcano Ranch experiment).

to be almost linear functions of lnE. Then for a mixed primary composition, according to the superposition principle of Peters (1960), they are linear functions of <lnA>. Consequently one expects to detect significant changes in <lnA> by observing changes in the experimentally measured rates of increase, $d(<x_m>)/d(lnE)$ and $d(<lnN_\mu>)/d(lnE)$.

The former is called the 'elongation rate'. The first systematic investigation capable of applying the elongation rate test indicated that <lnA> undergoes a large decrease in going from $\sim 10^6$ to 10^8 GeV (Thornton and Clay 1979). Since then the energy dependence of the elongation rate has been investigated by many groups using a wide variety of methods (Kalmykov et al. 1979, Antonov et al. 1979, Walker and Watson 1981, Chantler et al. 1982, Kvashnin et al. 1983, Alimov et al. 1983, Inoue et al. 1983, Cady et al. 1983). Although the later results are not all perfectly consistent, taken as a whole the <x_m> results require a decrease in <lnA> of 1.5 or more, which corresponds to changing from a mixed (low energy) composition to one highly proton enriched, between 10^6 and 10^8 GeV. In the region above this change, where the elongation rate test indicates little or no further change in <lnA>, the absolute value of <lnA> was found from a detailed analysis of <x_m> data to be $0^{+0.6}_{-0}$ Linsley and Watson 1981).

The other indicator, $d(<lnN_\mu>)/d(lnE)$, is less sensitive and more difficult to calibrate. The independent variable in actual experiments is N_e rather than E, but one expects N_e to be nearly proportional to E for given primary A, so the same principles apply. A change in composition will cause the value of $d(<lnN_\mu>)/d(lnN_e)$ to be less in a region where <lnA> is decreasing than it is where <lnA> is constant, but for low energy muons ($E_\mu < 10$ GeV) the expected change (corresponding to the variation in <lnA> described above) is only 8-10% (Grieder 1983). This is not much more than the uncertainty in the reference value (the value for <lnA> $\sim$ constant), and the actual sensitivity could be even less. In fact, $d(<lnN_\mu>)/d(lnN_e)$ for $E_\mu < 10$ GeV does not show any significant variations in the region where it has been studied, from $\sim 10^5$ to 10^8 GeV/nucleus. For higher energy muons the expected difference is greater, however, amounting to $\sim 15\%$ for $E_\mu = 220$ GeV. The only experiment on high energy muons capable of showing this kind of change has given results in good agreement with those from the <x_m> measurements (Acharya et al. 1983). A notable feature of this experiment is that the primary energy range extended down to 10^5 GeV; that is, to the region where <lnA> has been measured directly using balloons (Burnett et al. 1983, Sood 1983). This result and the one by Linsley and Watson are shown in Fig. 1.

Constancy of <lnA> in the interval 10^5-10^6 GeV is also indicated by data requiring other types of analysis: data on very high energy (TeV) muons (Elbert 1982, Battistoni et al. 1983, Matsuno et al. 1984, Allkofer et al. 1984), and on the energy spectrum of air shower hadrons, as analyzed by Grieder (1983, see also Dybovy and Nesterova 1983). Some other results on the hadron component have been seen as favoring a strong Fe enhancement in the interval 10^5-10^7 GeV (Goodman et al. 1979, Amenomori et al. 1983). However, like earlier claims for an iron anomaly at lower energies, these claims are not well enough supported to withstand the overwhelming weight of contrary evidence.

It should be noted that many of the indirect experiments are sensitive primarily to {lnA} rather than <lnA>. These experiments measure air shower fluctuations. The quantities that have been studied mainly are, again, x_m and N_μ. Unfortunately {lnA} is not very sensitive to the various assumptions that can be made about cosmic ray composition. If one assumes that the possibilities range from pure protons (<lnA> = 0) to pure Fe (<lnA> = 4), then the maximum value that {lnA} can have is 2, not much greater than the observed value in the low energy domain. Even a small admixture of protons with otherwise pure Fe, or of Fe with otherwise pure protons, will appreciably enhance the shower fluctuations so as to give {lnA} $\sim$ 1, which is about as low a value as any of the experiments have given. Experiments which measure the fluctuations of x_m escape this criticism somewhat because {x_m} is sensitive to <lnA> as well as {lnA} (Linsley 1983). The observed fluctuations above 10^8 GeV are consistent with pure proton primaries or with mixtures containing up to 50% of nuclei heavier than helium. They are not consistent with pure Fe primaries or with mixtures containing only a small percentage of light elements (Walker and Watson 1982, Dyakonov et al. 1983, Hara et al. 1983).

4. Conclusions. Below 10^5 GeV/nucleus the equal-energy composition varies with energy in the manner expected due to fragmentation in the interstellar medium with a rigidity dependent path length. The increase of <lnA> in this region is not a property of the sources, but is rather a propagation effect. Between 10^5 and 10^6 GeV there is little change in <lnA>. Between 10^6 and 10^8 GeV the average primary mass decreases to about 1 (<lnA> $\sim$ 0). It then remains constant, from 10^8 GeV to the highest observed energies (E $\sim$ 10^{11} GeV/nucleus).

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IMPLICATIONS OF THE EXPERIMENTAL RESULTS ON HIGH ENERGY
COSMIC RAYS WITH REGARD TO THEIR ORIGIN

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1. **Introduction.** In an earlier paper at this conference (OG5.4-4) by Linsley and Fichtel (1985), it was shown that current cosmic ray evidence supports a change in the cosmic ray composition in the region between 10^6 and 10^8 GeV total energy in the direction of a smaller average value of A. Compared to normal celestial abundances, the heavy nuclei are much less abundant, and, in fact, the composition measurements above 10^8 GeV are consistent with there being only protons. Here, these results combined with those of the energy spectrum and anisotropy of the cosmic rays and other astrophysical information will be examined to try to determine their implications for the origin of the cosmic rays. In the next two sections, there will be a consideration of the implications of one or more than one type of source in the galaxy to see which are consistent with the interpretation of current measurements. In the last section, the nature of the source types that would be required are discussed.

2. **Consideration of a One Source Type.** These sources would presumably be distributed throughout the galactic plane. The possibility of a single source at the galactic center or elsewhere is a special case. The most likely possible sources of cosmic rays, at least for the lower energies (10^6 GeV), appear to be supernovae and pulsars. Since the models generally envision the acceleration of the outermost layer (in the case of a supernova) or surrounding material (for a pulsar), there is not a major problem in reproducing the observed composition at lower energies at least in broad terms when subsequent fragmentation in the interstellar medium is considered.

Figure 1 summarizes current information on the observed total energy spectra. It is clearly not possible to obtain agreement with the all particle energy spectrum by assuming that all types of particles have an energy spectrum that continues as a power law with the same slope to arbitrarily high energies. It is also not reasonable to expect this to occur if these particles are galactic, because, even if they have such a spectrum at the source, there is a rigidity above which they cannot be held easily in the galactic arms in the plane (Peters, 1959; Fichtel, 1963). Using an estimated magnetic field value based on current information that is slightly smaller than used in the latter paper, that rigidity is estimated to be between 10^6 and 10^7 GeV. Clearly the steepening in the all particle spectrum at or somewhat below 10^7 GeV is consistent with this concept, and the change in slope at 10^{10} GeV (actually suggested by Fichtel, 1963, before it was reported by Linsley, 1963) may suggest an extragalactic component, although other

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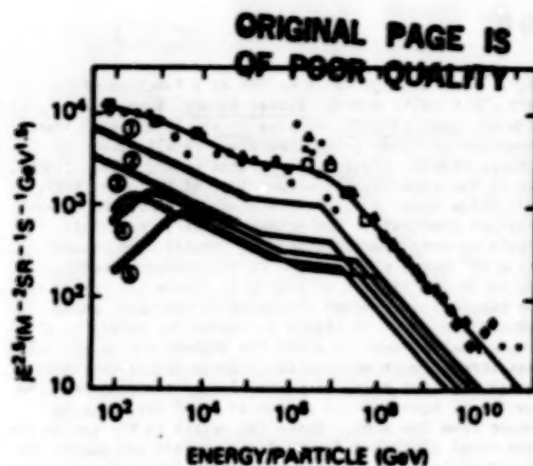
Fig 1: Cosmic Ray Particle Intensity as a function of kinetic energy per particle. The references corresponding to the symbols in the figure for nuclei of all types are as follows: closed square, Ryan et al.

(1972), Simon et al. (1980); and Burnett et al. (1983a): closed triangle, Burnett et al. (1983b); open circle, Grigorov et al. (1971); asterisk, Christiansen et al. (1983); open square, Efimov and Sokurov (1983); open triangle, La Pointe et al. (1968); closed diamond, Cunningham et al. (1980); closed circle, Bower et al. (1983). The circled numbers refer to the following 1 H (protons); 2 He; 3, (C,N,O); 4, (10 < Z < 20); 5, (21 < Z < 30). The hatched portion (++++) of the curves are based on a large number of balloon flight results, including: Ormes and Webber, (1965); Freier and Waddington, (1968); Lezniak and Webber, (1971); Webber et al. (1972); Ryan et al. (1972); Ormes and Balasubramanyan, (1973); Juliusson, (1974); Fisher et al. (1974); Arens and Ormes, (1975); Juliiot et al. (1975); Lund et al. (1975); Fisher et al. (1976); Hagen et al. (1977); Caldwell and Meyer, (1977); Maehl et al. (1977); Webber et al. (1977); Wefel et al. (1977); Lezniak and Webber (1978); Garcia-Munoz et al. (1979); Simon et al. (1980). The remainder of the curves are the cosmic ray particle intensity spectrum predicted for a single source model with a rigidity dependent escape, as explained in the text.

explanations are possible. Spectra which continue as a constant power law until a rigidity where particles begin to escape clearly, however, will not explain the moderate flattening of the spectrum from 10^5 to almost 10^7 GeV. As one approaches the rigidity where particles escape relatively easily, it is not unreasonable in a trapping and diffusion region to expect a lessening of the escape rate just below the rigidity where escape becomes relatively easy, as a result of the rigidity being large enough so that the smaller irregularities in the field are in effect not being seen by the particles. There must, of course, also not be a high intensity of large scale irregularities. One does not know if this is the situation, but it is at least plausible.

For Figure 1, a one source model was chosen with a power law of the form

$$j_z = A_z E^{-a} \tag{1}$$

for energies above the rounded portion of the maxima, and with the relative abundances shown as deduced from the balloon instrument results. The slope in Figure 1 may be interpreted as consisting of two parts, a and b, where a is given by equation (1) and b is a rigidity dependent escape term, as suggested by Ormes and Protheroe, (1983). Below 10^5 GeV, but above the rounded portion at low energies, the value of (a+b) used in Figure 1 is 2.7. Following this thinking and that of the last paragraph, b then decreases somewhat as escape becomes slightly less likely at 10^5 GeV and then increases markedly at 5×10^6 GeV. The values of (a+b) used in Figure 1 are 2.55 and 3.05 for 10^5 GeV $< 5 \times 10^6$ GeV and R $> 5 \times 10^6$ GeV respectively. It is now known (see, for example, Linsley, 1983) that there is an energy dependent anisotropy, which is consistent with a galactic population up to about 10^{10} GeV.

The measurements of the composition, or more exactly, the average value of the logarithm of the number of nucleons per nucleus, were discussed by Linsley and Fichtel (1985). The determined values of <lnA> as a function of energy are shown in Figure 2 together with the variation of <lnA> with energy predicted by the energy spectra shown in Figure 1. Clearly the curve, (a) in the figure and the data do not agree. It should be noted that the general shape of this curve, that is the rise to a higher value and then a leveling to a constant, is a result of the same source energy spectra for all nuclear species and a rigidity dependent escape. It does not depend significantly on the
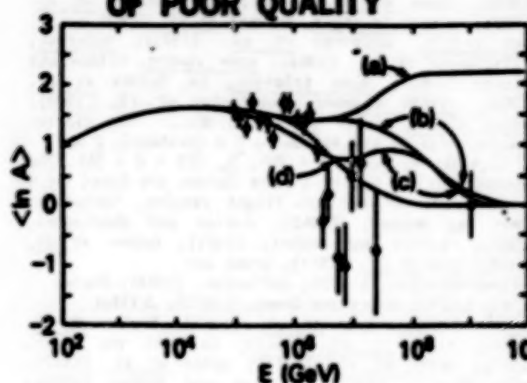
Fig 2: The average value of lnA as a function of particle kinetic energy. Closed squares, Burnett et al. (1983b); open circles, Acharya et al. (1983) with dip converted to <lnA> using simulation results given by Acharya (1983); closed circle, Linsley and Watson (1981). Due to the experimental errors some of the open circles fall below <lnA> = 0, in formal violation of the astrophysical constraint, for primary nuclei, that <lnA> should be zero (pure protons) or greater. The results below 10^7 GeV are normalized to the balloon results listed in the caption of Figure 1. Curve (a) refers to the single source model discussed in the text, whose spectra are shown in Figure 1. Curve (b) refers to a single source model in which the highest energy particles pass through much more matter. Curve (c) refers to the two source type model discussed in the text, wherein the spectra of both sources change at 3x10^6 GeV/C due to escape from the arms. Curve (d) refers to the two source type model discussed in the text, wherein one source has truncated spectra, which are shown in Figure 3.

source spectral shape. A possibility for a change in the composition of the type observed in a single source model is that it is a propagation effect. If, as seems almost certain, the magnetic fields in the Galaxy beyond the galactic arms are significantly weaker than in the arms and the matter density beyond 1 kpc from the plane is small, $<10^{-2}$ cm^{-3}, then the cosmic ray saturation density for the galaxy is well below that in the arms, and the lifetime is such that the matter traversed is very much less than that required to give the fragmentation of the heavy nuclei needed to cause predominantly heavy-nuclei-free cosmic ray composition above about 10^7 GeV.

3. Two Source Type Models. The introduction of two-source models is naturally aimed at avoiding the difficulties that have just been described. The discussion in this paper will be restricted to galactic sources being in the plane. Even subsequent acceleration models, which would not address the composition change at 10^6 to 10^7 GeV, are generally discussed in terms of the galactic plane. The basic concept which seems plausible is that one type of source dominates below about 10^6 GeV and the other above about 10^7 GeV with there being an overlap or transition region. As the apparently simplest assumption, the source type supplying the lower energy region will be taken to have the characteristics of the one-source-type model, but with no change in spectral slope until the escape from the galaxy. It will be assumed that the source at high energies, consisting of protons or mostly protons, whatever its origin, has a smaller slope, but also being a diffuse galactic source must have its steepening at the same rigidity as the lower energy type of source and by the same amount. An example of the results of this approach is shown in Figure 2 as curve (c), wherein the increase in slope due to escape from the arms occurs at $3x10^6$ GeV/C and the slope increases by 1.0 for all spectra. The energy spectrum matches well and the predicted <lnA> as a function of energy comes closer to the experimental values.

From an examination of the experimental data, however, it would appear that the composition may change at a somewhat lower energy; hence, either the escape rigidity must be overestimated or the lower energy source must not accelerate particles efficiently to quite this rigidity. If the escape rigidity is lowered significantly, it is not possible to obtain agreement with the total energy spectrum unless a more complex energy spectrum is assumed for the high energy source. The result for the total particle energy spectrum obtained by assuming that the lower energy cosmic ray spectra changes slope at $5x10^5$ GeV, while
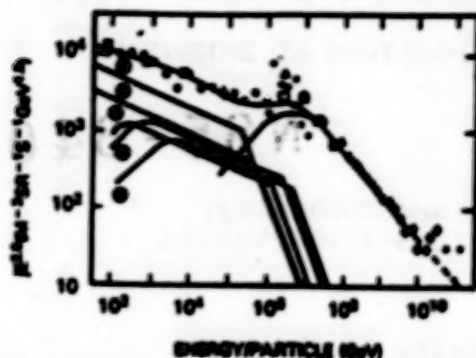
Fig 3: Cosmic ray particle intensity spectrum predicted by a two source type model in which the dominant low energy source has a source spectral change at 5x10⁶ GeV and the high energy source reflects a spectral slope change at 5x10⁶ GeV due to the effect of escape. The data are those referenced in Figure 1.

the higher energy source spectral change due to escape from the arms is around 5×10^6 GeV, is shown in Figure 3. The predicted behavior of the composition (lnA vs E) is shown as curve (d) in Figure 2. There is good agreement here with this broadened set of assumptions. Also, the increasing anisotropy is consistent with this model as it would be with any diffuse galactic source model as noted earlier. Should lnA not decrease as rapidly with energy as the data in Figure 2 show, as suggested by Nikolski and Stamenov (1983) and Dyakonov et al. (1983), the conclusions with regard to the nature of the two source types would be unchanged except that the higher energy source type would have more heavy nuclei. The significant point is that an acceptable two-source-type model seems possible.

4. What are the Two Source Types. As noted earlier, there seem to be several plausible theories to explain the cosmic rays comprising the component below about 10^6 GeV. The source of higher energy galactic cosmic rays must be able to accelerate particles to 10^{10} GeV. Further, this component is probably dominated by protons or may at most be a mixture of protons and relatively small amounts of helium and heavy nuclei compared to the celestial normal abundances. With regard to the composition, there seem to be at least two ways in which it might be achieved; the source could be a basically proton source (or produce neutrons which decay to protons), or the source could have a normal composition, but the particles could subsequently traverse enough material or photons in the source region to cause sufficient fragmentation of the heavier elements to leave a mixture of largely protons and some helium nuclei at least for part of the energy range. Possible source models include one associated with pulsars, although the highest energies are a difficulty, and a rapidly rotating massive black hole at the galactic center.

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THE PRIMARY COSMIC RAY MASS COMPOSITION AT ENERGIES

ABOVE 10^{14} eV

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1.   INTRODUCTION. It has been demonstrated by us (Gawin et al 1984) that the experimental data on EAS at the energy interval $10^{15} - 10^{17}$ eV seems to be described best if it is assumed that the Galactic cosmic rays are described by some sort of a two component picture. The first component is of a mixed composition similar to that at lower energies and the second is dominated by protons. Overall spectrum starts to be enriched in protons already at energies about 10^{15} eV but the effective mass of the primaries remains constant up to energies around 10^{16} eV. That results from the fact that composition gradually changes from multi-component to mixture of protons and heavies.

That picture receives also some sort of support from recent observations of relatively high number of energetic protons in JACEE and Concorde experiments (Burnett et al 1984 and Capdevielle 1984).

2.   THE MASS COMPOSITION FOLLOWING FROM TWO COMPONENT

PICTURE OF THE GALACTIC COSMIC RAYS.

The integral energy spectra of the primary particles of different masses are described by following expression:

$$J_A(> E) = (C_A/1.7) \; E^{-1.7} \; \exp(-(E/D_A)^2)(1 + E/3.33 \; 10^4)^{0.3} \; ,$$

insentity in $m^{-2} \; s^{-1} \; sr^{-1}$ and energy in GeV/nucleus.

A	C_A	D_A
p	$1.72 \; 10^4$	$3.33 \; 10^5$
α	$9.2 \; 10^3$	$6.67 \; 10^5$
CNO	$6.2 \; 10^3$	$2.17 \; 10^6$
H+VH	$9.2 \; 10^3$	$4.33 \; 10^6$
Fe	$6.2 \; 10^3$	$8.66 \; 10^6$

The integral spectrum of the additional proton component

$$J_p(> E) = 2.78(E^{-1} - 2.5 \; 10^{-7}) \; , \text{for } E \leqslant 2 \; 10^6 \; \text{GeV}$$
$$= 2.78 \; 10^6 \; E^{-2} \; , \text{for } E \geqslant 2 \; 10^6 \; \text{GeV} \; ,$$

3.   THE FLUXES OF HADRONS AT SEA LEVEL. We have already de-
monstrated (Kempa and Wdowczyk 1983) that the fluxes of hadr-
ons at mountain altitudes can be well described using the dis-
cussed here mass composition and the picture of high energy
interactions described elsewhere in this proceedings (HE- 1.2-
4). In figure 1 we have compared the fluxes of hadrons observ-
ed at sea level with predictions based on the above stated as-
sumptions. We can see that the agreement is moderately good.
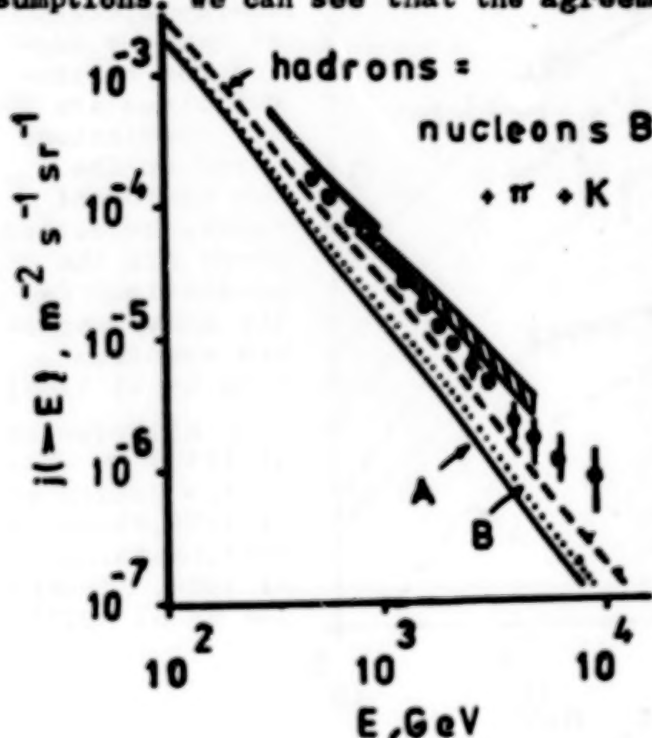
Fig.1. Hadron energy sp-
ectra at sea level. The
dotted line is the pred-
iction for the two comp-
onent spectrum B-flux of
nucleons for the two co-
mponent model and A- the
flux of nucleons for the
heavy enriched spectrum
(Tan et al 1982).($\bullet$-Sio-
han 1976,— Arvela et al
1981, Ashton et al and
Baruch et al 1977)

4.   FLUXES OF HIGH ENERGY MUONS. Under the same assumptions
about high energy interactions and primary particle mass comp-
osition we have calculated the fluxes of high energy muons in
the atmosphere. The fluxes were calculated taking formulae for
p-nucleus interaction, making detailed allowance for the muon
energy losses in the atmosphere and the losses due to the muon
decays. Probabilities of the decay were calculated taking into
account varying energy of muons with depth. Curvature of the
atmosphere was taken into account in the calculations for the
inclined direction. The results of calculations are compared
with experimental data in figures 2-4. In figure 2 the compar-
ison is made for muons recorded at ground level, in figure 3
underground at shallower depth and in figure 4 at large depths.
It should be pointed out that the good agreement seen in figu-
res is obtained without any normalisation. The predicted inten-
sities are plotted as they are obtained from the assumed prim-
ary spectra mass compositions and assumptions about the pictu-
re of high energy interactions. In figure 2 are also plotted
predictions obtained for the heavy enriched spectrum (Tan et
al 1982).

In calculations of the depth intensity curve the fluct-
uations in muon range were taken into account.

OG-5.4-6
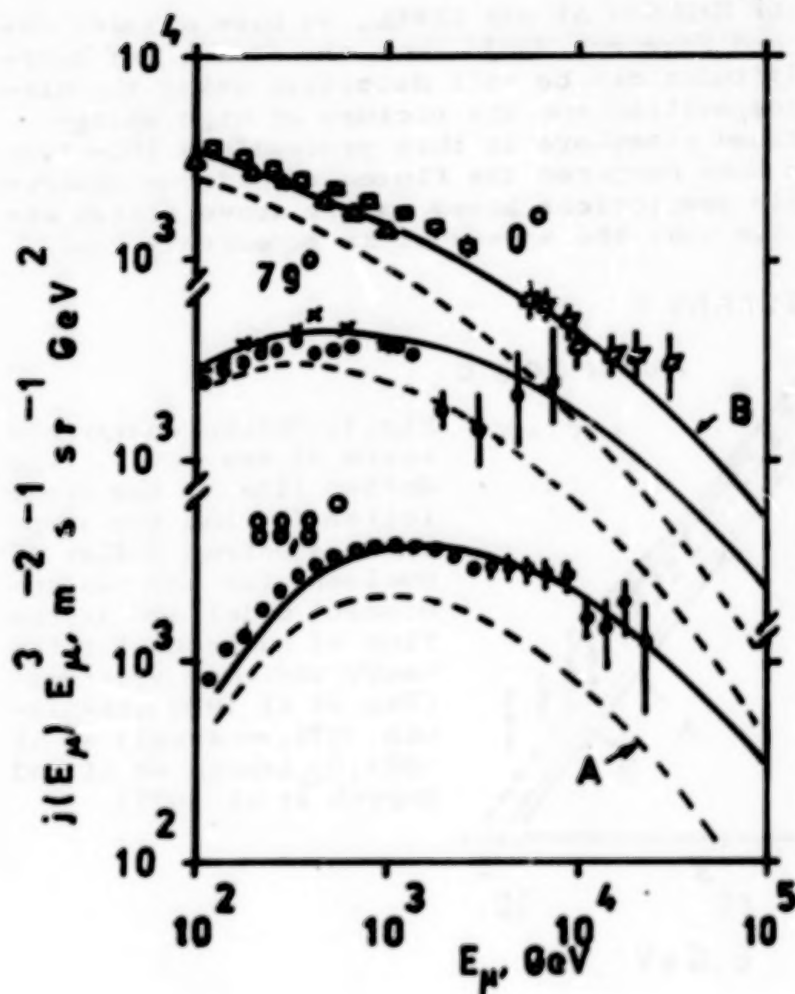
Fig.2. The muon energy spectrum at various angles. The continous lines are the predictions based on the two component model, the dotted lines are the predictions for the heavy enriched spectrum (Tan et al 1982)

(◆ Allkofer et al 1981, △ ----1971, ⚹ Jokish et al 1979, ◊ Khrenov 1977, ◊ Matsuno et al 1984, ○ Thompson et al 1977)
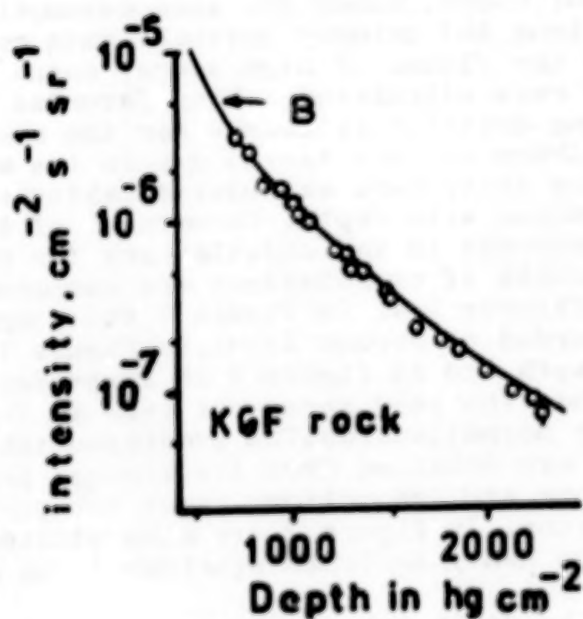
Fig.3. Depth intensity curve (after Krishnaswamy 1981) for shallow depths compared with that calculated from the muon spectrum obtained by us (B).

OG-5.4-6
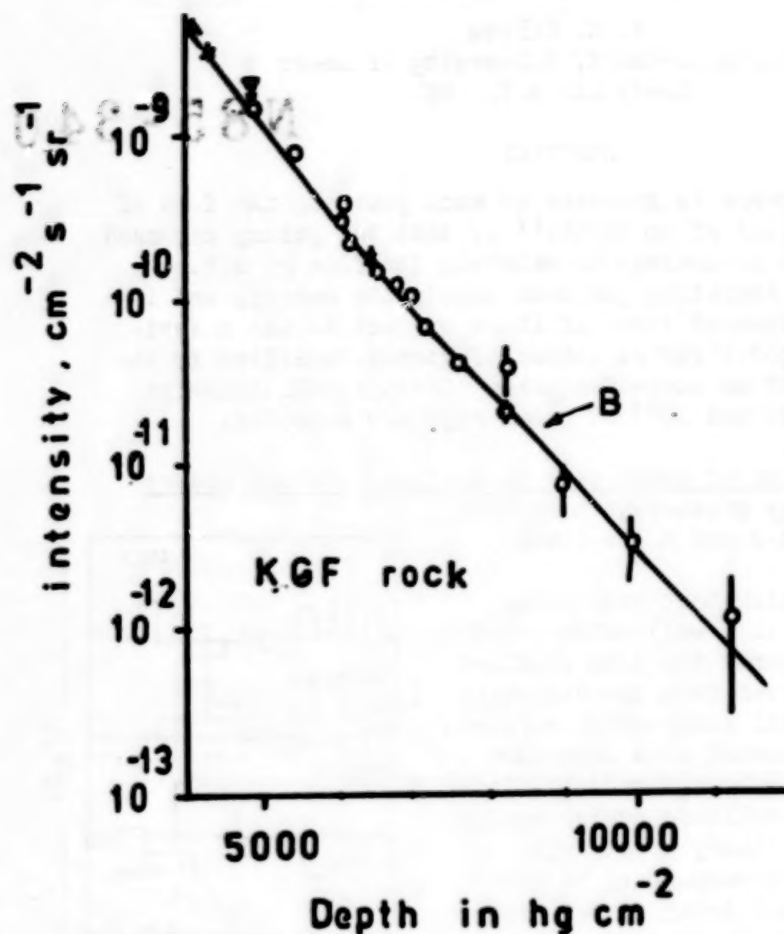
Fig.4. The same as in figure 3 but for the greater depths.

5. CONCLUSIONS. We have demonstrated that the fluxes of high energy secondary particles observed in atmosphere can be well predicted on the basis of the two component picture of the Galactic cosmic ray and the picture of high energy hadron - nucleus interaction deduced from the accelerator data.

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U.H.E. PARTICLE PRODUCTION IN CLOSE BINARY SYSTEMS

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ABSTRACT

Cygnus X-3 appears to generate so much power in the form of charged particles of up to $\sim 10^{17}$ eV that the galaxy may need $\lesssim 1$ such source on average to maintain its flux of u.h.e. cosmic rays. Accreting gas must supply the energy, and in a surprisingly ordered form, if it is correct to use a Vest-rand-Eichler model for radiation of gammas, modified by the introduction of an accretion wake. Certain relationships between 10^{12} eV and 10^{15} eV gamma rays are expected.

1. Evidence for emission of gamma rays at distinct orbital phases

Ultra high energy gamma-rays have been observed from Cygnus X-3 and a few other X-ray binary sources.

First, to establish that underlying the variability there is a well-established pattern, Figure 1 compares the time profiles of the radiation observed from the direction of Cygnus X-3 by several independent workers. The flux (usually presented as a departure from the normal all-sky background) is plotted (on an arbitrary amplitude scale) against phase of the 4.8-hour binary orbit, with phase zero, as usual, corresponding to the minimum intensity of the X-ray signal, presumed to be when the X-ray source near a supposed neutron star is partly hidden behind the larger companion star. Apart from the early but very lengthy data set 1, the phase in all plots has been calculated from the X-ray data of van der Klis and Bonnet-Bidaud — the orbital period slowly changing with time. The observers do agree on brief periods of emission during the orbit: the 10^{15} eV observations indicated a burst of gamma-ray emission near phase 0.25 in the orbit, whilst at 10^{12} eV the main emission occurs near phase 0.63. However, during the lengthy Crimean observations, the phase of the main emission would switch between roughly these two regions (though the exact alignment of the phase plot from this early date is difficult). And the latest 10^{15} eV observations at Haverah Park (this conference) show the emission much stronger around the 0.63 peak. The Whipple Observatory (Mt. Hopkins) observers have demonstrated considerable month-to-month variability in flux (and two of their time profiles
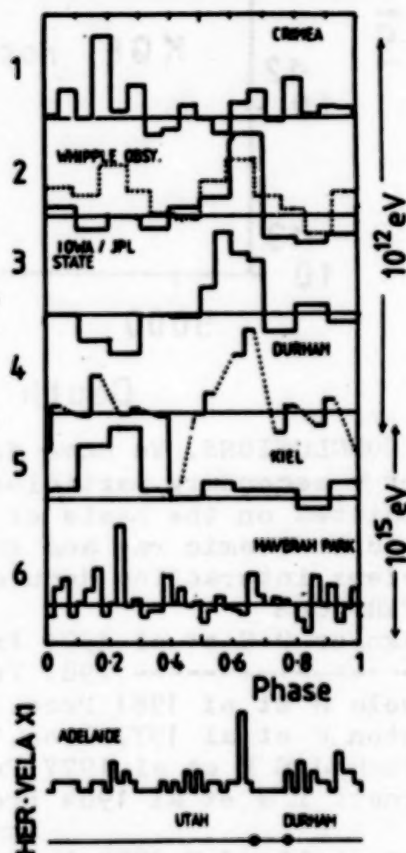
Figure 1. (Refs 1-6) Occurrence of gamma rays from Cygnus X-3 vs orbital phase. Below: Vela X-1 phase plot (7), and observations of Her X-1.

are shown): year-to year variability is also found at Haverah Park.

The particles causing the observed air showers are taken to be photons because (a) they are uncharged, being deflected $<2^{\circ}$ in the 12 kpc or so from Cygnus X-3, (b) they do not decay in the 40,000 year journey, eliminating neutrons and neutral atoms (which would become ionized), and (c) the time dispersion <0.15 orbital period implies a Lorentz factor $>1.5\times10^{4}$: if the threshold energy is 0.5 TeV, $m_{primary} < 33$ MeV. (For Her X-1, the 1.2-second modulation implies a time spread $\lesssim 1.5$ sec after 5 kpc (1 TeV): $m < 3$ MeV. For the Soudan mine radiation, not discussed here, if $E_{prim} \sim 5$ TeV, $m_{prim} < 400$ MeV.)

2. Mode of production of the gamma-rays

The basic process put forward by Vestrand & Eichler (8) is still basically the most promising, but it requires modification. In its original form, this model had a neutron star in orbit around the companion, and accelerating protons to high energies, emitting them (roughly) in all directions, and those few that grazed the top of the atmosphere of the large star would suffer nuclear collisions and generate neutral pions and hence gamma-rays. Just at certain points in the orbit, a distant observer would see gamma rays briefly as the source passed behind the star, and later as it re-emerged. At phase 0.25 we might be seeing the re-emergence pulse if the atmosphere were swollen by gas emission. However, a pulse near phase 0.8 is dubious, whilst the prominent pulse at $\sim$0.63 occurs when the neutron star is well to the front of the companion!

This latter phase may not be an accidental feature, as the (sole) report of gamma rays from Vela X-1 (Figure 1) shows sharp emission at the same phase. Is there a gas target in this direction? This is in fact the direction in which an accretion wake is expected if accretion occurs from a stellar wind (see Figure 2). Such a wake is seen as an X-ray absorption in Cen X-3, for instance (9). If the radial wind has a speed v_w and the n-star orbital speed is v_0, the wake will lag behind the outward radius by an angle $\tan^{-1}(v_0/v_w)$: i.e. 45° if $v_w = v_0$ — appearing at phase 0.625, or 35° (phase 0.60) if $v_w = v_{escape} = \sqrt{2}v_0$.

To support the V & E model, one may note that the gamma ray spectrum extends to 10^{16} eV, but that gamma rays cannot pass

Figure 2. Supposed geometry for Cygnus X-3.

through a region where $B_{\perp} > 4\times10^{18}$ eV/E_{γ} gauss — about 400 gauss in this case. As statistical particle acceleration to such energies is unlikely (especially in weak fields) on the available time scale (10), it is highly probable that the particle acceleration occurs in a region of stronger (e.g. pulsar) field than this, so the gamma rays are produced in a place outside the acceleration region — i.e. on a "target". Electrons are unlikely to survive the strong fields involved in acceleration to 10^{17} eV: hence the assumption of protons (10).

The observation of brief gamma-ray emission from Her X-1 at the time (11) interpreted as the moment of reappearance of the n-star from obscuration by a dense accretion disc also supports a gas-target picture in the case of this source.

3. Significance for cosmic rays, of magnitude of power output

(a) The cosmic ray power output of Cygnus X-3 may be estimated roughly as follows. Above 10^{15} eV, the Haverah Park flux is $\sim 3 \times 10^{-14}$ photons cm^{-2} s^{-1}: these bring an energy flux 1.1×10^{-10} erg cm^{-2} s^{-1} per decade (e.g. in the decade to 10^{16} eV). The published time profile indicated a pulse duty ratio ~ 0.02, so if there had been a suitable gas target in place all round the orbit the photon energy received would have been 50 times this. Allowing for absorption of a factor 3 (by pair production on primeval radiation) en route, an efficiency $\sim 1/6$, say, for converting proton energy to gammas, a source distance $r = 12$ kpc, and supposing the particles appear in a solid angle Ω, the total power emitted in the proton beam is

$$W = (\Omega/4\pi) \times 6 \times 3 \times 50 \times 1.1 \times 10^{-10} \times 4\pi r^2 = (\Omega/4\pi) \times 1.7 \times 10^{39} \text{ erg s}^{-1} \text{ per decade.}$$

The proton spectrum must extend to $\sim 10^{17}$ eV to produce photons up to 10^{16} eV, and most of these protons should escape into the galaxy. To maintain the present flux of galactic cosmic rays above 10^{16} eV the galaxy probably needs an energy input $\sim 5 \times 10^{37}$ erg s^{-1} above 10^{16} eV (12) — based on a roughly estimated trapping lifetime $\sim 2.5 \times 10^5$ years at this energy (12). Hence one such object active for only part of the 10^5 year storage time could supply the galaxy's flux of 10^{16}-10^{17} eV protons.

(b) *Accelerated spectrum?* Perhaps the neutron star can generate a power-law spectrum of protons (like the observed gamma spectrum), but alternatively, for direct (non-statistical) acceleration it may emit most of its power near the upper energy limit — say 10^{17} eV, the roughly $E^{-2}dE$ spectrum of gamma rays resulting from cascading in the target area. (It has been shown elsewhere (12) that if a magnetic field exceeding a few tens of gauss is present in the target area one can generate a cascade rapidly by synchrotron radiation following pair production, without needing very much matter — and the result has a spectrum very much like the overall gamma spectrum from Cygnus X-3.) The power in the 10^{17} eV protons then has to be sufficient to supply the energy in several decades of gamma rays.

If such a powerful source is indeed not often present, we are evidently lucky to see it! Is the existence of other sources then an embarrassment? The other 10^{15} eV sources in this galaxy (Vela X-1 and Her X-1) are in fact much weaker — but there may turn out to be many more. If the accelerated beam is quasi-monoenergetic , one must indeed expect a greater number of sources that emit particles of lower energy, to yield the known cosmic ray spectrum: there must be more TeV sources. Is the source 4U 0115+63 — found to be intense at 10^{12} eV (preprint from Turver's group) but not seen at 10^{15} eV — a member of such a population? The evolutionary history needed to explain the overall spectrum of particles in the galaxy is as yet unknown, and it is not apparent that a power law would emerge in any simple manner.

(c) *Mode of acceleration?* Acceleration by a large-scale emf generated by moving conductors in a strong magnetic field seems most likely, but the pulsar action of the neutron star itself is probably inadequate, (i) because Cygnus X-3 is probably an old n-star, whose rotational energy store would have run out long ago, and (ii) Vela X-1 has a spin period of 5 minutes, from X-ray evidence — much too feeble. Hence the accreting matter is presumably supplying the energy and also the high speed necessary. (See also (13)). However, the particles we detect are not emitted near the normal to the orbit (or to the Her X-1 disc), but closer to the

plane of the disc (or at least the orbit) — probably closer to Michel's
(14) picture than Lovelace's. It is remarkable that the particle power
is not small compared with the X-ray power — as though accretion energy is
efficiently converted to electrodynamic energy rather than heat.

4. Possible observations

If the gamma-ray spectrum is generated by cascading from 10^{17} eV
protons, the TeV gammas are seen where the gas target is thicker, and the
10^{15} eV gamma pulse should appear somewhat displaced — at the tenuous
edge of the gas (but with much overlap). (To check this, contemporaneous
measurements are needed, as the exact pulse position wanders somewhat.)

The phase of the prominent pulse, on this picture, is determined by
the angle of the accretion wake; hence wandering of the wake probably
signals changes in wind speed and may be related to variations in source
power, and possibly to impending outbursts.

If the upper limit of the gamma spectrum is limited by transmission
through a magnetic field (15) rather than by the primary proton beam, it
is likely to be different for the pulse at phase 0.25 (generated close to
the large star) and that near 0.63 — generated well away from the star.

If, as widely believed, there is a stellar wind in Cygnus X-3 that
has a significant optical depth to X-rays — say 5 g cm^{-2} — ~10% of the
protons will interact even outside the special "gas target" positions,
giving a widely spread weaker flux of gamma rays. If this is not present,
it will constrain the angle into which the protons are emitted, and we may
then need to explain the pulses in terms of real directional acceleration
of the charged particles. (This has seemed less likely at present, unless
the particle acceleration occurs so far away from the neutron star that
the position of the companion plays a part in determining the field orient-
ation.)

Puzzle: Where are the X-rays generated? The source must be very large
if it is not occulted by the gas target that is being supposed to intervene
at phase 0.63: the X-ray intensity is a maximum here (unlike Cen X-3).

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VIRGO CLUSTER AS A HIGH ENERGY COSMIC RAYS SOURCE

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ABSTRACT

The extragalactic charged particles are reflecting from the Galaxy by its magnetic field. Assuming magnetic field in the Galaxy as quasilongitudinal we have evaluated mean transparency of Galaxy for extragalactic protons defined as a fraction of particles at a given energy from a given direction passing by the galactic plane. The anisotropy caused by the Galactic magnetic field reflection of protons can explain observed arrival directions of EAS at large angle to the galactic plane. Our analysis shows that the increase with energy observed in $<\sin b^{II}>$ is self-consistent with changing in the cosmic ray energy spectrum at high energy $(E > 10^{19}$ eV) in the case when extragalactic cosmic ray source with spectral index -2.2 is at the position of the Virgo Cluster.

I. INTRODUCTION

The measurements of energy spectrum and anisotropy of cosmic rays are the basic source of information about its origin. The main difficulty to identify the cosmic rays sources is the Galactic magnetic field. In the past we analized propagations of cosmic rays protons emmited by Galactic sources distributed as Galactic matter (Karakuła et al., 1972). The comparison of the calculated and observed extensive air showers (EAS) anisotropy shows that if protons are the primary cosmic rays of energy greater than 10^{18} eV they should be predominantly extragalactic. The study of EAS (i.e. Watson, 1980: Linsley and Watson, 1981) shown that cosmic rays at energies above 10^{19} eV are likly to be of extragalactic origin. The anisotropy of arrival directions of the highest energy cosmic rays is observed from the directions of the large angle to the galactic plane $(b^{II} \approx 74°)$ (Cunningham et al., 1980 and 1983). The experimental data confirmed the flattening of the cosmic ray energy spectrum at energy greater than 10^{19} eV and the exponent of the integral energy spectrum is -1.4 ± 0.1 (Cunningham et al., 1980 and 1983: Bower et al., 1983).

In this paper we have considered the cluster or supercluster origin of high energy cosmic rays model, but for lower energy $E < 10^{18}$ eV we assumed Galactic location of cosmic ray sources. For the quasilongitudinal magnetic field in the Galaxy we have evaluated the mean transparency of the Galaxy for extragalactic protons. Our analysis shows that the increase with energy observed in $<\sin b^{II}>$ (Cunningham et al., 1980) is self-consistent with changing in the cosmic ray energy spectrum at high energy $(\gtrsim 10^{19}$ eV) in the case when extragalactic cosmic ray source with spectral index -2.2 is at the position of the Virgo Cluster $(b^{II} = 74°)$.

2. THE TRANSPARENCY OF THE GALAXY FOR EXTRA-GALACTIC PROTONS

The trajectory of arriving protons from the particular extragalactic directions were calculated assuming the mathematical model of the magnetic field in the Galaxy. In our calculations the magnetic field in the Galaxy was assumed as the quasilongitudinal model of Thielheim and Langhoff (1968). In this model the field lines are parallel to the spiral arms but with opposite orientation above and below the galactic plane. The strength of the component of the field parallel to the arms in details was described in our paper Karakuła et al., (1972). The galactic disc, where the trajectories of protons were calculated, was defined by $|z| \leq 0.4$ kpc (distance perpendicular to the galactic plane) and $R \leq 15$ kpc (radius from the Galactic Center). The equation of motion of the protons in the Galactic magnetic field was solved numerically. Our calculations indicated that some of the extragalactic particles are reflecting from the Galaxy by its magnetic field. Only extragalactic particles entering the Galaxy on the observing level can be registrated as an EAS. We have evaluated the mean transparency of the Galaxy which was defined as a fraction of the number of particles at a given energy from a given position of source passing through the plane located at a Solar System and perpendicular to the direction of the extragalactic source (observer plane). In practice for large b^{II} this plane is the galactic disc plane ($z=0$). We have followed large number of the protons trajectories for selected energies. The positions of the starting point of the protons trajectories was at random selected on the plane outside the Galactic disc. The real magnetic field in the Galaxy has a regular and irregular components (magnetic clouds). Our model of the magnetic field in large scale describes the regular component. The nature and feature of irregular component are not known up to now. For our considerations we also assume that the general properties of this component should be weaker than the regular component and should follow the last one in whole Galaxy. So from the point of view of our considerations there is no difference between random occuring irregularities of magnetic field in the time of protons propagation and at random selected positions of the starting point of the proton trajectory for the model of regular Galactic magnetic field. Moreover in that case we evoid the problem
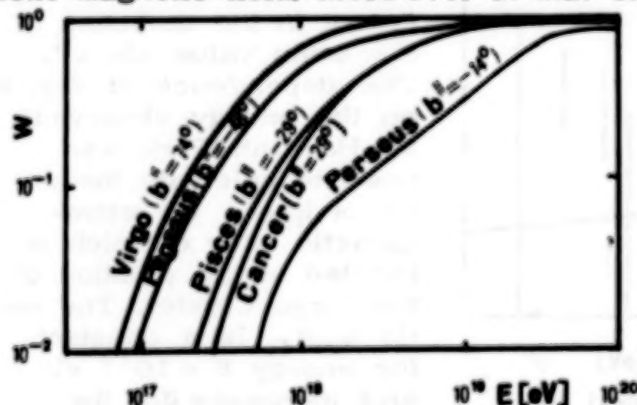
Fig. 1. The mean transparency of Galaxy as a function of proton energy.

of focusing of particles in quasilongitudinal magnetic field. The mean transparency parameter defined above is characteristic for the whole Galaxy. Figure 1 shows the mean transparency of Galaxy for extragalactic protons for the selected directions of the group of galaxies. The transparency of Galaxy increases with energy. We can also notice that the energy of pro - tons, when galactic mag-

netic field has a small influence on particles, strongly depends on the arriving positions relative to the Galactic plane.

3. THE EXPECTED FLUX OF THE COSMIC RAYS FROM THE VIRGO CLUSTER

The base of our analysis was the Haverah Park EAS data (Cunningham et al., 1980) indicating that the mean value of $\langle \sin b^{ll} \rangle$ increases with energy.

In this paper we want to examine if the observed changes in energy spectrum of cosmic rays and $\langle \sin b^{ll} \rangle$ are self-consistent, as far as our simple assumptions allow:

i) the galactic cosmic ray differential energy spectrum (I_G) for energy greater than 10^{19} eV has a power index -3.1,

ii) some extragalactic sources with an unknow spectrum (I_{Ex}) located at a position b_o^{ll} can give contribution to the observed flux,

iii) the probability of the registration of the extragalactic charged particles depends on its energy, because of the influence of the Galactic magnetic field.

In such case the mean value of $\sin b^{ll}$ can be expressed by:

$$\sin b^{ll} = \frac{\int I_G \cdot P(b^{ll}) \cdot \sin b^{ll} \cdot db^{ll} + w(b_o^{ll}) \cdot I_{Ex} \cdot P(b_o^{ll}) \cdot \sin b_o^{ll}}{\int I_G \cdot P(b^{ll}) \cdot db^{ll} + w(b_o^{ll}) \cdot I_{Ex} \cdot P(b_o^{ll})},$$

where:

$P(b^{ll})$ – the probability of registration by Haverah Park array as the function of b^{ll},

$w(b^{ll})$ – the transparency of the Galaxy versus energy for extragalactic protons.

The integral in the numerator of above expression gives the con - tribution from the galactic cosmic ray flux. The second component of this sum represents the contribution from the extragalactic point source located at the position b_o^{ll}, after integration over the galactic latitude with the delta Dirac function. The denominator expresses

the normalization coefficient in the definition of the mean value $\sin b^{ll}$. The dependence of $\langle \sin b^{ll} \rangle$ on the energy observed by Haverah Park was used to calculate the ratio of I_{Ex}/I_G for extragalactic source which is located at the position of the Virgo Cluster. The ratio I_{tot}/I_G is a constant for energy $E < 10^{19}$ eV and increases for the greater energy. Fig. 2 shows the differential total $(I_{tot} = I_G + I_{Ex})$ cosmic

Fig. 2. The total flux (multiplied by E^3) calculated from $\langle \sin b^{ll} \rangle$ as a function of energy.

ray flux multiplied by E^3 calculated from Haverah Park measurements of $\langle \sin b_0^{II} \rangle$.

4. DISCUSSION AND CONCLUSIONS

From the comparisons of our results (Fig. 2) with experimental data of cosmic ray energy spectrum (Cunningham et al., 1980: Hillas, 1984) we can conclude good agreement. We have made the same calculations for different positions (b_0^{II}) of the extragalactic point sources but the best agreement we have got only for the position of the Virgo Cluster. It can be strong indication that high energy cosmic rays ($E > 10^{19}$ eV) are originated from this cluster. We can also notice that the differential cosmic rays energy spectrum of the Virgo Cluster has the spectral index $\approx$ -2.2, and in the energy range $\approx 10^{18}$ eV the intensity of the Galactic and extragalactic fluxes are equal. In the lower energy region the Galactic cosmic ray flux is dominand.

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MODELING COSMIC RAY ANISOTROPIES NEAR 10^{18} eV

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ABSTRACT

A galactic magnetic field reversal near the Sagittarius
spiral arm may be responsible for the southern excess
(or northern shortage) of cosmic rays near 10^{18} eV. The
north-south asymmetry produced by such a reversal would
increase with energy in the same manner as the observed
asymmetry [1,2]. The existence of a reversal has been
inferred from analyses of Faraday rotation measures [3,4].

I. The puzzle. Cosmic ray fluxes in the EeV range (1 EeV=10^{18} eV)
display a prominent anisotropy. The flux is suppressed at northern
galactic latitudes, and the effect increases with energy through the
decade .5-5 EeV [1,2]. This measured anisotropy should be instrumental
in any attempt to piece together a picture of the Galaxy's magnetic
field and the sources of high energy cosmic rays. Other pieces of
this puzzle are the following:

1. The cosmic rays at this energy are probably mostly protons.
This is based mainly on studies of the depth of maximum of air showers
and the variance in the depths of maximum [5].

2. The mean galactic magnetic field near the sun has a
magnitude of about 2.2 µG, and at least near the sun it is directed
clockwise about the galactic center as viewed from north of the Galaxy
[6]. Protons moving perpendicular to the field lines have orbit
diameters $D = E$, where E is the energy in EeV and D is in kpc. The
energy decade .5-5 EeV therefore provides probes up to distances of 5
kpc.

3. The sources of these cosmic rays are probably galactic. By
virtue of Liouville's theorem, the anisotropic observed flux cannot
come from an isotropic extragalactic flux. If the extragalactic flux
is not isotropic but is coming primarily from the Virgo cluster, then
it is very difficult to explain how the anisotropy could be turned into
a southern excess over a whole decade of energies. It is conceivable,
though, that some of the cosmic rays in this energy decade are coming
from the southern side of the Galaxy (rather than from the Virgo
cluster). For example, acceleration by galactic wind termination
shock [7] might occur between the Galaxy and the Magellanic clouds
and could preferentially fill the southern half of an extended halo.
If the ordered magnetic field were confined to a thin enough disk, then
a southern excess would be expected as these particles diffuse north-
ward. Any such model would be rather contrived, however, since it
would require a southern source to be prominent only in a limited
energy band where no remarkable spectral bump is observed. In the
following we will assume that EeV cosmic rays are of galactic origin.

4. The magnitude of the disordered part of the galactic magnetic field is not much greater than the mean (ordered) field strength, even in dense clouds [8,9]. An abrupt large-angle change in a particle's direction is therefore rare. The scale of magnetic irregularities probably does not exceed 150 pc [10]. For EeV protons whose orbit circumferences are several kiloparsecs, the orbits therefore sense primarily the mean field but suffer frequent small deflections from magnetic irregularities.

5. The ordered galactic magnetic field is probably not confined to a thin disk, but may extend 3 kpc or more to either side of the plane. If the ordered field were confined to a thin disk of 1 kpc full thickness, for example, then at energies above 1 EeV no proton orbiting perpendicular to the field direction could be confined. At several EeV a pronounced excess would be detected from directions nearly parallel or anti-parallel to the field direction. Moreover, just below 1 EeV, protons orbiting perpendicular to the field lines would be confined only if their orbits met the galactic plane nearly perpendicularly. In particular, arrivals from the galactic center and anti-center directions would be strongly suppressed. In evaluating the thickness of the ordered magnetic field, it would be helpful to have not only the observed dependence of flux (at various energies) on the north-south variable (galactic latitude) but also the mean flux values projected onto the galactic center-anti-center axis as well as flux values projected onto the axis parallel to the mean field direction.

6. Analyses of Faraday rotation measures [3,4] suggest that a reversal of the ordered field occurs between the sun and the galactic center. Various estimates exist for the distance to the reversal, but a distance of 2 kpc may be realistic. Field reversals of this type are seen in other spiral galaxies (M51, M33, M81, NGC 6946, NGC 4258) [11,12]. Among the spiral galaxies whose fields have been mapped, M31 is exceptional in not showing a field reversal [13,14].

II. Assembling a picture.   Putting together pieces 4 and 5 one finds that EeV cosmic rays are governed by a large-scale ordered magnetic field. In this context Hillas [15] has made the following cogent argument that a southern excess at Earth implies the existence of a radial gradient in the cosmic ray density: Liouville's theorem requires that the intensity (per unit area and solid angle) from the south at point P in figure 1 must equal the intensity from the north at earth. The observed southern excess at earth then implies that the intensity from the south at earth exceeds the intensity from the south at P. Similarly, the intensity from the north at Q exceeds the intensity from the north at earth. Therefore the northern and southern intensities increase with galactic radius. It can also be shown that if the density of cosmic ray orbit centers increases linearly with galactic radius near the sun, then the observed north-south asymmetry should increase linearly with energy (i.e. orbit size).
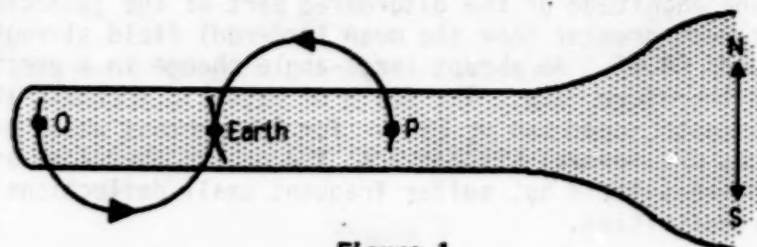
Figure 1

If the orbits shown in Hillas' figure are proton orbits at 4 EeV (where the southern excess is very prominent), then points P and Q are separated by 8 kpc. Even if one considers trajectories of median pitch angle, the inferred radial gradient persists over 4 kpc. A source density variation over such large distances would not be due simply to variation within or between spiral arms. We know of no reason why high energy cosmic ray sources should be more abundant at larger galactic radii.

If the cosmic ray density gradient is not due to a source gradient, then it must be due to some propagation effect. Instead of excess sources outside the sun's galactic orbit, one can look for a sink region closer to the galactic center. A field reversal region is an effective evacuation site for cosmic rays. Figure 2 shows some of the fast-escaping trajectories near a reversal. (The shaded regions are regions where grad$|B| \neq 0$.)
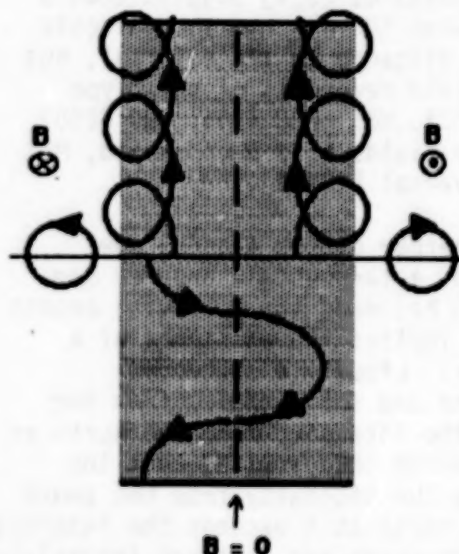
Figure 2

The field reversal zone is then a region of low cosmic ray density, so a density gradient points away from that region (radially outward at the sun's position). Orbits of very high energy cosmic rays could be affected directly by the field reversal, causing a pronounced shortage at high northern latitudes.

Our numerical simulations confirm that the energy dependence of the northern shortage (southern excess) can arise from a uniform source density if there is a field reversal at about 2 kpc with a gradient region of .5 kpc on either side of it and if there is some admixture of isotropic flux from the halo or intergalactic space.

III. Remarks.   A definitve explanation for the northern shortage of EeV cosmic rays may not be possible without more detailed knowledge of the galactic magnetic field and cosmic ray sources. If careful analysis determines that the ordered magnetic field is, after all, confined to a thin disk, then a planar excess model [16] (i.e., shortage at north and

south poles) might be a complete explanation for the anisotropy. Or perhaps it will be found that a significant fraction of EeV cosmic rays are heavy nuclei, in which case a spiral arm source density gradient could be the correct explanation. In fact, each puzzle piece is rather fuzzy. In support of the field reversal explanation, we only claim that it is a picture which is composed of the pieces described above and which requires no special ad hoc pieces.

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Anisotropy and the Knee of the Energy Spectrum

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1. Introduction The measured cosmic ray energy spectrum exhibits clear
structure (the knee) at ~ 3 x 10^{15} eV (sea level shower size
~ 3 x 10^5 particles). Additionally, at energies in this general region,
there occur apparent changes in shower development such that the
observed characteristics of showers at this energy appear different to
those characteristics observed at somewhat higher energies (see eg.
Linsley 1983). At energies just below this region, the cosmic ray
anisotropy amplitude apparently begins a progressive increase with
energy. The latter effect does not clearly fit with the first two since
there appears to be no significant change exactly at the knee. However,
the _phase_ of the first harmonic of the anisotropy appears to show a
substantial change just where the energy spectrum shows structure and in
the middle of the shower development changes. The first harmonic phase
appears to change from ~ 18 hours R.A. to ~ 5 hours R.A. (see eg. Clay
(1984)) as the energy of observation moves through the knee. In this
paper I wish to examine the latter change in some detail by taking into
account information contained in the second harmonic of the anisotropy.

2. Anisotropy measurements near the Knee Anisotropy measurements at
one location are not sufficient to define the true celestial anisotropy
since only a limited range of declinations is observable at a given
latitude. This limitation is particularly severe for air shower arrays
which use scintillators to sample the electron-photon component since
atmospheric attenuation with increasing zenith angle is severe. This
effect was useful for collimation in early experiments. Available
anisotropy results are therefore, unfortunately, rather incomplete with
measurements being biased towards temperate latitudes with convenient
land sites. The overall sky coverage of most experiments is ~ 20° to
60° N and ~ 15° to 40° S. At ~ 10^{15} eV, just below the knee, there is
a good deal of agreement between the various experiments on the observed
phase of the first harmonic. This is remarkable because the southern
observations really view an independent part of the celestial sphere to
the northern observations.

There is an ambiguity in anisotropy results presented in terms
of first harmonics. A sine wave is fitted to the data in right
ascension but there is no information on what properties of this fourier
component are of physical significance. It is not obvious, although it
is conventionally stated, that the phase of the _maximum_ of the fitted
wave is physically appropriate, unless, for instance, one is interested
in searching for the superposition of a number of high energy gamma ray
sources. In the latter case, the anisotropy maximum will indicate a
direction with an excess of sources. However, for the diffusion of

charged particles, the position of maximum on the celestial sphere will
give the direction of the "upstream" diffusion direction and there will
be a minimum in the "downstream" direction. In general, a particular
declination will not include both the upstream and downstream directions
leading to an ambiguity for latitudes which include observation of only
the downstream direction.

I have pointed this out before (Clay 1984) and shown that, on
the basis of the observed directions of first harmonic maxima at
~ 10^{15} eV , one might interpret the global data as representing a
diffusive flow of cosmic rays along the galactic spiral arm. In order
that this be so, it is necessary that, at energies below the knee, the
southern hemisphere phase of the first harmonic <u>minimum</u> is the
physically interesting parameter since this represents the direction
towards which diffusion is occurring. Other explanations of the overall
anistropies at these energies are possible and one suggestion has been
that they may be due to unresolved ultra high energy gamma ray sources
(Wdowczyk and Wolfendale 1983). A test between these possibilities
would be to see whether or not there is any additional reason in the
data for the first harmonic minimum to appear to be more physically
significant rather than the maximum.

In the diffusive model, since the spiral arm is of limited
extent in the sky, one would expect a relatively sharp peak of the
anisotropy in the source direction and a similar trough in the
downstream direction. In the gamma ray source model, only positive
effects due to an admixture would be expected and no particular sharp
dips or peaks would be necessary. In the latter case, one might in
general expect only a diffuse excess for general galactic directions
unless only specific galactic region contained the most powerful
sources. An examination of the second harmonic can help resolve these
possibities.

<u>3 Inclusion of the Second Harmonic</u>   Figure 1 shows data obtained by
Farley and Storey (1954). The phase of the first harmonic maximum is
indicated and it would appear that there is no particular significance
in this phase. The total data set can be described quite well with the
inclusion of the second harmonic as illustrated. Also, an examination
of figure 1 suggests that the region at about 8 hours is likely to be
physically interesting rather than the 20 hour phase. This is in the
vicinity of the <u>minimum</u> of the first harmonic.

Fig. 1   Data presented by
Farley and Storey 1954. The
combination of their first
and second harmonics are
included   (unnormalised)
together with an indication
(arrow) of the phase of the
first harmonic maximum.

0h   6h   12h   18h   24h
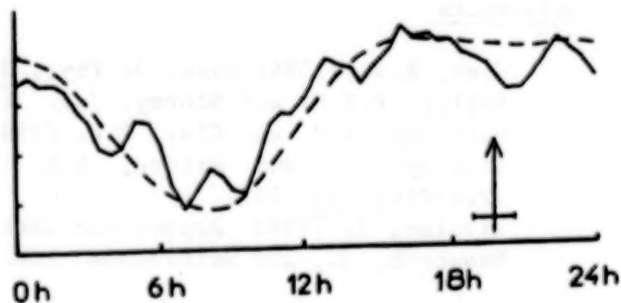
I have examined the data included in the compilation of
anisotropies by Linsley and Watson (1977) and have also included more
recent Adelaide data (Gerhardy and Clay 1983). Where appropriate I have
combined data from similar latitudes and energies and have added first
and second harmonics to derive representations of the original data in
terms of R.A. or sidereal time. I then examined these distributions to
see whether or not they subjectively contained a peak or a trough and,
at what celestial direction this occurred. Some results of this
procedure are shown in figure 2 with peaks indicated by + and troughs
by −.

Fig. 2   The positions of
peaks (+) or troughs (−) in
anisotropy data available
for energies ~ 10^{15} eV.
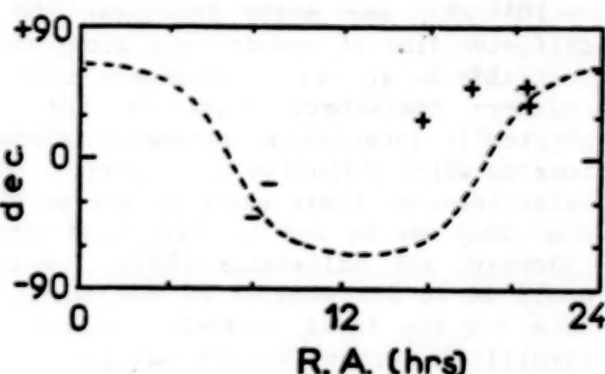
Figure 2 indicates that this procedure lends weight to the
hypothesis that the cosmic ray flow below the knee is diffusive with its
source in the inward spiral arm direction. There are peaks from a
number of experiments clustering generally in that direction and there
are also apparently troughs in the opposite direction from independent
experiments in the other hemisphere.

At higher energies, the situation is much less clear. It
seems to me likely that the statistical uncertainty in detail of the
anisotropy is such that the technique cannot be used for such small data
sets where the overall flux is low.

4. Conclusions When anisotropy results are presented in terms of the
phase of first harmonic maximum, that particular direction may not be
the physically significant direction for the data set. Additional use
of the second harmonic can clarify this when data with sufficient
statistics are available. It appears that, at least at 10^{15} eV, cosmic
ray anisotropy data are most compatible with diffusion along the galatic
spiral arm from the inner to outer galactic regions.

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ANISOTROPY OF COSMIC RAYS ABOVE 10^{14}eV

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ABSTRACT

A survey is made of the anisotropy of cosmic rays at
energies above 10^{14}eV. It is concluded that cosmic γ-rays
may have an effect in the range 10^{14}-10^{16}eV, above which
protons dominate. Evidence is presented for an excess in
the general direction of the Galactic plane which grows
with increasing energy until about 10^{19}eV, indicating a
Galactic origin for these particles. At higher energies
an Extragalactic origin is indicated.

1. Introduction. Many surveys of cosmic ray anisotropy measurements
have been made in recent years and a consistent picture is emerging as
to the manner in which the amplitude of the first harmonic and its phase
varies with energy. In our own work (Wdowczyk and Wolfendale, 1984a,b)
we have extended the analysis to a study of both first and second
harmonics and separately for the northern and southern hemispheres.
Figure 1 gives the results for the amplitudes and Figure 2 concerns the
phases.

It is our objective to explain the observed trends; this can be done
most conveniently by energy range.

2. The range 10^{14}-10^{16}eV. Inspection of Figure 2 leads us to suggest
that for E : 10^{14}-10^{16}eV we are dealing with a region where γ-rays con-
tribute significantly to the anisotropy, this suggestion following on
earlier work (WW 1983) which in turn was prompted by the Cygnus X-3
observations. Gamma ray sources are expected preferentially at small
Galactic longitudes and this feature appears in Figure 2 (viz. the
shaded area near ι = 0° for 10^{14}-10^{16}eV). At higher energies γ-rays
are apparently unimportant insofar as the anisotropy is concerned.

3. 10^{16}-10^{19}eV. A different feature appears at higher energies. Between
about 5.10^{17}eV and 10^{19}eV there appears to be an enhancement centred on
the Galactic plane but as the energy falls the pattern appears to be
rotated. Figure 3 shows the situation. The obvious explanation is that
we are dealing here with charged particles; the change of φ with falling
energy is in the sense of that expected due to the curvature of the
local magnetic field lines (the field analysis having come from earlier
work by Karakula et al., 1972, Osborne et al., 1973, and Ellis and
Axon, 1978).

4. Energies above 10^{19}eV. In our earlier work (WW 1984a,b) we defined
a Galactic plane excess parameter, f_E, defined by I(b) = I(0) {(1-f_E
+ f_E exp-b') where b is the Galactic latitude. The analysis shows that
f_E rises with energy, being ∼ 0.1 at 10^{18}eV, 0.3 at 5.10^{18}eV and 0.6
at 2.10^{19}eV. However, at the very highest energies, f_E appears to drop

(to ≈ 0.25) indicative of the bulk of the particles being extragalactic, a result that is in accord with other work.
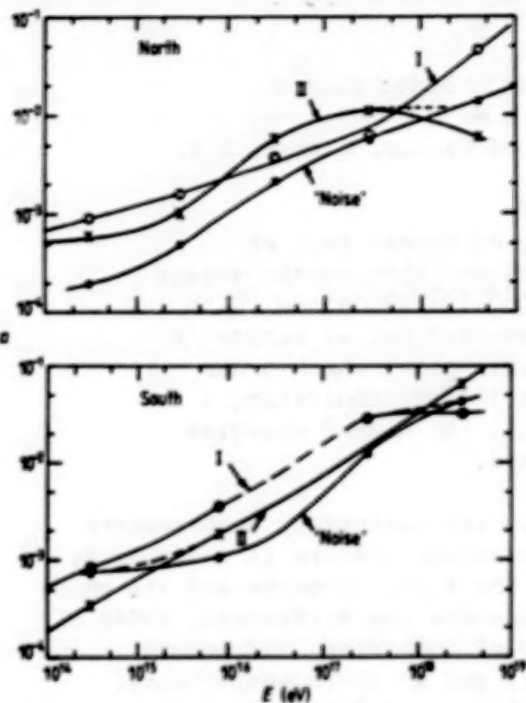
Fig. 1. Amplitudes of the first (I) and second (II) harmonics of anisotropy measurements averaged over successive decades of energy. The measurements in the Northern hemisphere (upper part) were from extensive air shower arrays located at latitudes from 43°N to 62°N. Those in the Southern hemisphere (lower part) cover the range 16°S to 37°S. The curve denoted 'noise' relates to expectation from a true distribution with zero anisotropy, measured isotropies arising simply by chance. The significance level is one standard deviation.
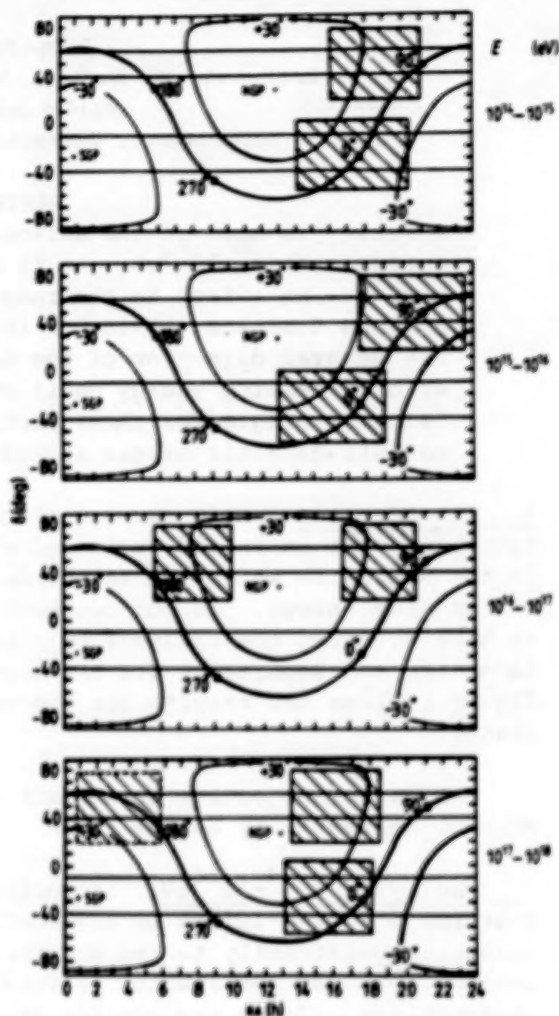
Fig. 2. Celestial plots showing the directions from which much of the excess flux arises. The data suggest the presence of an excess associated with the Galactic plane in the Inner Galaxy for the energy region 10^{14}-10^{16}eV. At higher energies the excess from the Inner Galaxy moves to Northern Galactic latitudes, reaching $b \approx 30°$ for the range 10^{17}-10^{18}eV.
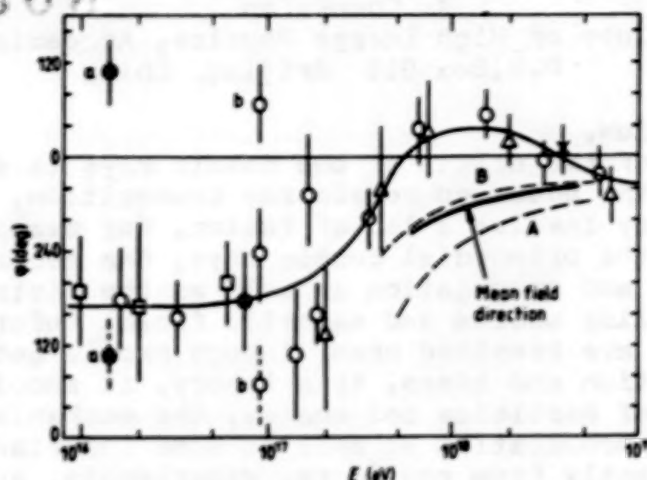
Fig. 3. Angle ϕ through which the prediction of the
Galactic plane excess should be rotated in order
to fit best the observed pattern of intensity
against RA (after WW, 1984a). The points marked
'a' and 'b' are plotted twice. The full curve is
intended to guide the eye. The broken curves
give the directions from which detectors in the
Northern hemisphere should record maximum inten-
sities using the Galactic magnetic field models
of Karakula et al. (1972). The data available
on the very local field direction, which allows
for irregularities, give the line indicated 'mean
field direction' - for comparison with the trend
of ϕ it should be displaced to lower energies by ~ 3.

5. Conclusions. The present analysis suggests that γ-rays play a key
role in explaining the trend of anisotropy phase with energy in the
range 10^{14}-10^{16}eV. Very recently support has come from the Backsan
experiment (Alexeenko and Navarra, 1985) but the hypothesis cannot be
regarded yet as completely proven: a 'Galactic ridge' of muon poor
showers with high precision is a pre requisite. Above 10^{16}eV the
behaviour of the anisotropy with energy is indicative of charged part-
icles providing the bulk of the anisotropy, those below 10^{19}eV being
Galactic and the very highest energies extragalactic in origin.

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OG 5.4-12

A MODEL FOR THE PROTON SPECTRUM AND COSMIC RAY ANISOTROPY

N85-34089

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1. Introduction.

The problem of the origin of the cosmic rays is still uncertain. Since the observed cosmic ray composition, spectrum and anisotropy involve a lot of factor, for example, the spectrum of the primordial cosmic rays, the mechanism of acceleration and propagation as well as the distribution of the interstellar medium and magnetic field. Unfortunately, all of these are remained open, though people gets more and more information and ideas. As a theory, it should explain the support of particles and energy, the mechanism of acceleration and propagation as well as some important features obtained directly from cosmic ray experiments, such as the power spectrum and the knee at about 10^{15}eV[1], the near constant amplitude of the first harmonic of anisotropy among 10^{11}-10^{14}eV and the amplitude varying as $E^{0.5}$ above 5×10^{15}eV[2,3]. And it should also account for the relative abundance and the flux of cosmic rays. But so far there is no model which can interpret all of these phenomena.

In a general opinion the cosmic rays of 10^{10}-10^{18}eV are the galactic origin,but above they are the extragalactic origin. People also acceptes that the cosmic rays propagate in a diffusion way, variaty of diffusion mechanism derive different diffusion coefficient as a function of energy. But anyhow diffusion always makes the energy spectrum steeper.

There are two kinds of models for interpreting the knee of the cosmic ray spectrum. One is the leaky box model[1] in which every nuclei has different escape starting rigidity,the heavier the higher, but the flux of heavy nuclei is much less. Another model[4] suggests that the cut-off rigidity of the main sources causes the knee. The present paper studies the spectrum and the anisotropy of cosmic rays in an isotropic diffuse model with explosive discrete sources in an infinite galaxy.

2. The transport equation and its solution.

In an isotropic diffusion model cosmic ray density,$N(r,t,E)$, obeys the following equation[5]

$$\frac{\partial N}{\partial t} - D\nabla^2 N + \frac{\partial}{\partial E}(NW) + BN = Q. \tag{1}$$

where D is the diffusion coefficient, the third term is due to energy loss, $W=dE/dt$, the fourth term is negitive source and Q is the source. Firstly, starts our argument from one discrete source and assume as follows:

(1) Because the ages of the main point sources within 1kpc (table.1) are about 10^4y[6], even for the highest energy proton its half lifetime(caused by Compton scattering, synchrotron radiation and bremstruhlung altogether) is several

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decades to few hundred times long as its age. So we neglect the energy loss.

(2) Assume the P-P interaction contributes to the negtive source term only, $B=cn\sigma_{int}$, where c is the speed of light, n the density of hydrogen, σ_{int} the inelastic cross-section of P-P interaction. From accelerator experiments[1] the total cross -section of P-P is obtained among energy range 10-1.5x10^2 GeV, and $\sigma_{int}=0.8\sigma_{tot}$. Fitting these data, get the formula

$$B(E)=3\times 10^{-17}\{35.3-2.2(\ln E)+0.3(\ln E)^2\} \ (1/s). \quad (2)$$

here n =1 has been taken.

(3) The charged cosmic rays propagate through resonant scattering with the turbulent hydromagnetic wave. Zhang et al[8] derived

$$D=\frac{1}{12\pi}\frac{\beta}{\sqrt{1-\beta^2}}\frac{\bar{B}}{e}\frac{mc^2}{\Lambda\varepsilon_0}.$$

rewrite it as

$$D=\frac{Pc}{12\pi}\frac{\bar{B}c}{e\Lambda\varepsilon_0}. \quad (3)$$

where $\bar{B}$ and ε_0 is the mean intensity and energy density of the fundamental

Table 1. List of SNR near the solar system

NAME	t(10^4 y)	r(kpc)	E (eV)
CTB 72	3.2	0.7	2x10
Cyg. Loop	3.5	0.6	10
HB 21	4.3	0.8	3x10
CTB 1CT	4.7	0.9	2x10
CTB 13	3.2	0.6	10
HB 9	2.7	0.8	2x10
S 149	4.3	0.7	10
Monoceros	4.6	0.6	7x10
Vela	1.1	0.4	10
Lupus	3.8	0.4	4x10
Loop	3.0	0.05	10

magnetic field, respectively. Λ is the fraction of turbulent in the mean field. Take $B=3\mu G$, $\Lambda=0.01$, $\varepsilon_0=0.3eV/cm^3$, then for the proton of greater than 10GeV,

$$D=1.67\times 10^{11}E(cm^2/s).$$

In general the coefficient has a form $D\propto E^{1/2}$, say $E^{0.5}$, but the recent data from HEAO-3 show that the index trends to rising and $D\propto E^{0.7}$ can account for the experimental data quite well. A compare shows that the diffusion coefficient adopted by our paper is close to that with the index 0.7 at high energies.

(4) The i-th point source ejects particles transiently with a spectrum $N_0 E^{-\Gamma}$ at t=0. So that $Q=N_0 E^{-\Gamma}\delta(r-r_i)\delta(t)$

Combining of all these and transforming $N=\mathcal{N}e^{-Bt}$, we get solution of Eq.(1)

$$N_i=\frac{N_0 E^{-\Gamma}}{(4\pi Dt_i)^{1.5}}\exp[-\frac{r_i^2}{4Dt_i}-B(E)t_i] \quad (4)$$

where t_i is the age of the point source, r_i the radial distance with its origin at the source position. Mathematically, the formula(4) makes sense for any value of r_i and t_i, but considering the causality only such sources with $(r_i/t_i)<c$ contribute to the observed flux. So we take account such sources only.

3. The predict spectrum of proton.
From Eq.(4) see that for very old/and distant pointsource its density N_i has a very large Gaussian width, i.e. $\nabla N_i=0$, so we can treat them altogether as a background N_b. Therefor

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we have

$$N = N_b + \sum N_i \qquad (5)$$

supposing v is isotropy and neglecting higher than second harmonic anisotropy of I, then $N = 4\pi I/v$, we have

$$I = I_B + \sum I_i \qquad (6)$$

Taking the parameters $=1.5$, $N=4 \times 10^{47}$, $I_B = 2.5 \times 10^4 E_{eV}^{-1.5}$ (m.s.sr.GeV)$^{-1}$
and inserting these values of r_i, t_i, of the eleven supernovas in Eq.(6), we have the result(Fig.1). You can see that the predict results fits the data of the proton quite well. In fact, because of the cut-off energy of the eleven supernovas, the value of I_B is almost uniquely determined by the data of the proton of 10^{11}-10^{13} eV. It is clear that the time scale of change of the proton intensity $\tau > 1/cn\sigma_{eg} = 10^7$ y, it agrees with long time data of cosmic rays.

4. The anisotropy of cosmic ray.

Under above mentioned case, the amplitude of first harmonic anisotropy has been obtained

$$\vec{\delta}_i = (\frac{3r_i N_i}{2ct_i N}) \vec{\tau}_{oi} \qquad (7)$$

where r_i is the unit vector from the Earth to the i-th point source. Considering the motion of the Earth with respect to the cosmic ray background there will be Compton-Getting anisotropy, independent of energy but relevant to the spectrum index

$$\vec{\delta}_c = (\gamma+2)v/c \qquad (8)$$

so the final resultant anisotropy, can be expressed as

$$\vec{\delta}_I = \vec{\delta}_c + \sum_i (\frac{3r_i}{2ct_i})(\frac{N_i}{N}) \vec{\tau}_{oi} \qquad (9)$$

The experimental data show that

O Proton-4, □ Tien Shan, ● Haverah Park, ◇ Yakutsk,

Fig. 1 The differential spectrum of primary cosmic rays Curve 1 is the sum of intensities contributed by eleven supernovae. The dashed line represents the background I_B. Curve 2 is the predicted differential spectrum of primary protons. Shaded area and sign □ are the data of protons, the rest are somewhat contaminated by other nuclei.

Fig.2. The expected amplitudes of the anisotropy caused by eleven SNR individually.

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$$N=4\pi I/c=1.2\times10^3 E^{-2.66}(1/m^3) \quad \text{for } E\leqslant5\times10^6 GeV$$
$$N=1.1\ E^{-3.1}(1/m^3) \quad \text{for } E>5\times10^6 GeV$$

Inserting these values of r_i, t_i, N_i of the eleven supernovea individually and the value of N into Eq.(7), using the trial values $N_0=1.32\times10^{46}$, $\Gamma=1.2$(corresponding to the source emission 10^{50} ergs in the particle form),the anisotropies as a function of energy were calculated.The results are given in Fig.2.

We find that each of these anisotropies is smaller than 6×10^{-5} below $10^4 eV$, but varies as $E^{0.4}$ above $5\times10^3 eV$.So whatever the direction of each anisotropy is, the resultant anisotropy always has a $E^{0.4}$ variation. On hte other hand, the measured anisotropies are about 5.5×10^{-4} in the energy range $10^{11}-10^{14}eV$. Combination of these information together leads us to draw the conclusion that the Compton-Getting anisotropy is dominant, $\delta=\delta_c=5.5\times10^{-4}$ below $10^{14}eV$.By substituting$\gamma=2.66$ in Eq.(8), we get the velocity of 35km/s with respect to the cosmic ray background.

5. Discussion and conclusion.
The anisotropy mentioned above is in principle for proton. However, the anisotropy is dependent on the species of cosmic rays.Unfortunately,so far the identification of the species of cosmic ray in EAS is uncertain yet.Recently,a few of discreteγ-ray sources in the energy range $10^{13}-10^{16}eV$ has been detected.People have noted the possible effect of γ-rays on the anisotropy and the intensity of cosmic rays[9].

The conclusion to be drawn from this study may be summarized as follows: Taking some reasonable parameters,the model can account for the features of the proton spectrum and the approximate constancy of the cosmic ray intensity in a long period.It also can interprete the power law of the anisotropy above energy $5\times10^{15}eV$,and the Compton-Getting effect is responsible for the anisotropies in the energy range $10^{11}-10^{14}$ eV. Furthermore, we got the streaming velocity of 35km/s with respect to the cosmic ray background.

Finally, I am grateful to Prof.A.W.Wolfendale for his helpful discussion and useful information.

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INTERPRETATION OF COSMIC-RAY ANISOTROPY BELOW 10^{14} eV

N85-34090

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We have found that the measured data on the degree
of anisotropy of cosmic rays are consistent with
our proposed nonuniform galactic disk model. Moreover,
we point out that the abrupt increase of the
anisotropy of cosmic rays beyond 10^{14} eV should
imply a change of their mass composition.

It appears that a nearly constant degree of anisotropy of cosmic rays (δ) below 10^{14} eV is in conflict with the usual leaky box model(1). Thus it is interesting to examine the cosmic-ray anisotropy calculation in our proposed nonuniform galactic disk (NUGD) model(2).

In the NUGD model the observed δ value should be characteristic of the magnetic tube (Box 1 in Fig. 1 of OG 7.2-10), because the solar system is assumed to be located inside it. Along the magnetic tube cosmic-ray protons should present a streaming motion. It is adequate to describe this motion by using a one-dimensional slab model

$$\frac{dN_{pI}}{dx_I} = - \frac{N_{pI}}{\lambda_p^i} + \int_{E_p}^{\infty} \frac{1}{\lambda_p^i} \frac{dN_p(E_p,E_p')}{dE_p} N_{pI}(E_p')dE_p' , \qquad (1)$$

where N_{pI} is the proton intensity in Box 1, x_I is the pathlength travelled by cosmic rays along the magnetic tube, E_p is the total energy of a proton, λ_p^i is the mean inelastic interaction length of interstellar protons and $dN_p/dE_p = 1/E_p'$ is the energy distribution of protons after their inelastic interactions with the interstellar medium(ISM). At high energies the diffusive motion approximation of cosmic rays means

$$x_I = x_{0I} E_p^{-\delta_e} , \qquad (2)$$

where x_{0I} is a constant and $\delta_e = 0.7(3)$. Eq. (1) then can be reduced to

$$\frac{dN_{pI}}{dx_I} = - \frac{N_{pI}}{\lambda_p^{att}} , \qquad (3)$$

where $\lambda_p^{att} = \lambda_p^i /(1- 1/\gamma_p)$ and γ_p is the differential spectral exponent of the high-energy proton spectrum. Hence in the solar neighbourhood the proton intensity N_{pIs} should be

$$N_{pIs} = N_{pOI} \exp(- x_{0Is} E_p^{-\delta_e} /\lambda_p^{att}), \qquad (4)$$

where N_{pOI} is the initial value of N_{pI} and $x_{0Is} = 0.4 \lambda_p^i$ (4). For $E_p \geqslant 10^{11}$ eV the mean gradient of cosmic rays along the magnetic tube is
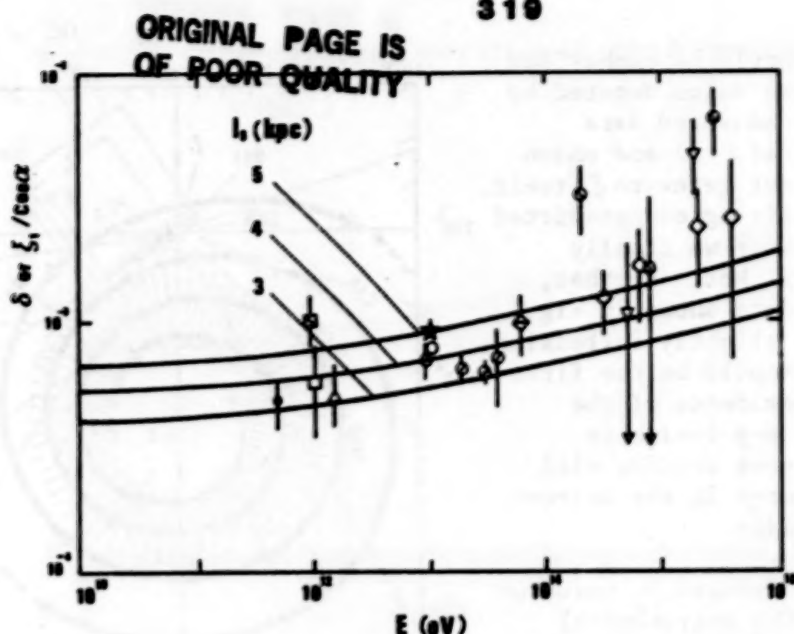
Fig. 1

$$\frac{1}{N_{pI}} \frac{dN_{pI}}{dl_I} = \frac{x_{Is}}{l_s \lambda_p^{att}} \quad , \tag{5}$$

where l_s is the distance along the magnetic tube between the H_2 cloud region and the solar system. Under the diffusive motion approximation of cosmic rays we also have

$$\tau_{Is} = l_s^2 / 2\kappa_I \, , \tag{6}$$

where κ_I is the diffusion coefficient of cosmic rays in Box I and τ_{Is} is the transit time to reach the solar neighbourhood. Since

$$\tau_{Is} = x_{IS} / (m_p \bar{n}_I c), \tag{6}$$

where m_p is the proton mass, $\bar{n}_I$ is the mean hydrogen atom density of the ISM in Box I and c is the velocity of light, we can get

$$\kappa_I = m_p \bar{n}_I c l_s^2 /(2x_{Is}) \, , \tag{8}$$

and the degree of anisotropy of cosmic rays(5)

$$\delta = \frac{3\kappa_I}{c} \frac{1}{N_{pI}} \frac{dN_{pI}}{dl_I} = \frac{3m_p \bar{n}_I l_s}{2 \lambda_p^{att}} \, . \tag{9}$$

It is interesting to note that in Eq. (9) the increase of the cosmic-ray diffusion coefficient with energy is just compensated for by the opposite variation of the cosmic-ray intensity gradient, so that a nearly constant δ value should be obtained. In Fig. 1 the predicted δ curves are based on $\bar{n}_I = 1.2$ H atoms cm^{-3} (6) and the value of λ_p^I suggested in Ref. (7). An additional increase of λ_p^{att} is included to take the contribution of heavy nuclei in the ISM into account. From Fig. 1 the scattering of l_s values estimated from various data is found to be within $\approx \pm 1$ kpc.

However, it should be emphasized that except the datum denoted by a star(8) the measured data collected in Ref. (9) and shown in Fig. 1 do not refer to δ itself. Thus by normalizing our predicted curve to the star we finally obtain l_s = 5±1 kpc. Further, the measured data shown in Fig.1 indeed show a slightly increasing trend, which should be the first astronomical evidence of the rising of the p-p inelastic interaction cross section with increasing energy in the context of the NUGD model.

From our deduced l_s value we can estimate the astronomical counterpart of our model elements. In Fig. 2 the geometrical relationship between the H_2 cloud ring (the radially hatched region) and the large-scale interstellar

Fig. 2

magnetic field (the spirally solid lines) is shown. As the reversal of field direction occurs between the Orion arm and the Sagittarius arm, a neutral line should exist between both arms. The existence of a neutral line should obstruct the exchange of cosmic-ray particles between two adjacent arms. As a result, in the H_2 cloud ring only from a narrow region exterior to the Sagittarius arm (the region II in Fig.2) cosmic-ray particles can stream along the Orion arm to reach the solar neighbourhood.

Actually, in our model picture each small region including a dense H_2 cloud and its magnetically connected surrounding gas may be viewed as a coherent entity which is called as a cell(10). All the magnetically connected cells form a subtube and all subtubes form the magnetic tube. In view of the fluctuation of interstellar magnetic field the direction of the subtube, in which the solar system is located, may be different from the general direction of the Orion arm. Thus the measured value of the maximum phase for the 1st harmonics of cosmic-ray intensity variation may be understood.

It is noticeable that in order to avoid affecting the spectral shape of heavy nuclei, the NUGD model requires an assumption that in the distant component of cosmic rays there should exist a serious deficit of heavy nuclei. Actually, similar assumptions also appear in many other double-component models of cosmic-ray propagation. However, in our model the deficit should occur in the preacceleration stage of cosmic rays (e.g., by an unfavourable preacceleration condition for heavy nuclei in their acceleration sites above the H_2 cloud region). Thus the observed heavy nuclei of cosmic rays should be of local origin. Moreover, from an analysis of the high-energy electron spectrum(4) it is found that only about 5 % of observed protons come from the local region.

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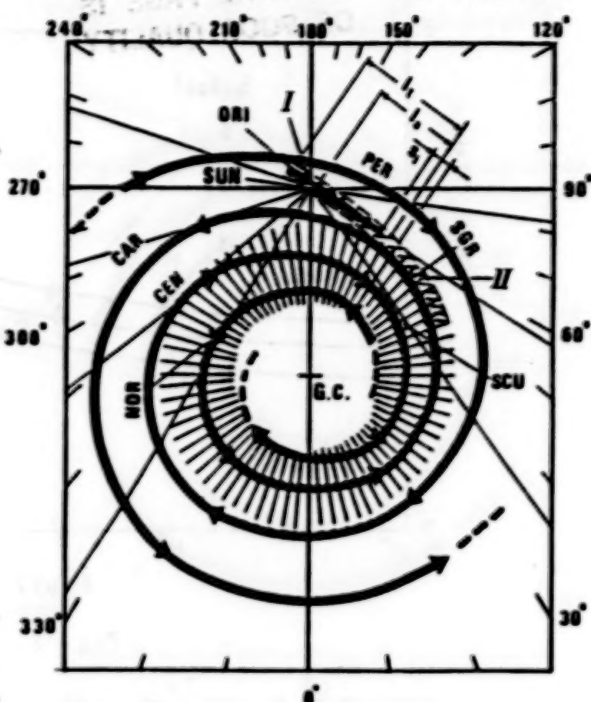
Consequently, in the sample of locally produced cosmic rays the abudances of heavy nuclei relative to protons must be higher the directly observed values by a factor of 20. The assumed relative abudances of cosmic-ray nuclei in the sample of locally produced cosmic rays are shown in Fig. 3 as the horizontal lines. In Fig. 1 we have noted that an abrupt increase of the degree of anisotropy of cosmic rays occurs beyond 10^{14} eV. Here we try to attribute this increase to the failure of our NUGD model due to the insufficient confinement of cosmic rays at very high-energies. Therefore, at very

Fig. 3

high energies the locally produced cosmic rays would fill the intensity vacancy left by the distant component of cosmic rays. As a result, the observed abudances of cosmic-ray nuclei should approach to the local abudances shown in Fig. 3. In view of the situation that above 2×10^{15} eV the dominant contribution to the observed cosmic rays may come from one single source, these abudaces may never be reached. Nevertheless, a variation of cosmic-ray mass composition with increased contribution of heavy nuclei should be expected to happen around 10^{15} eV.
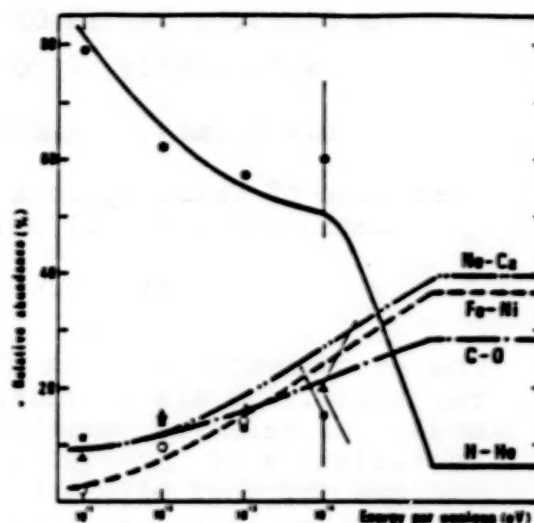
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ON GALACTIC ORIGIN OF COSMIC RAYS
WITH ENERGY UP TO 10^{19} eV   N85-34091

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Abstract

The experimental data on ultrahigh energy cosmic
ray anisotropy are considered. In supposed
models of galactic magnetic field the main cha-
racteristics of expected anisotropy are estimated
and are compared with the experimental data.
In is shown that particles with energy up to
10^{19} eV are of galactic origin.

Spectrum. The observed spectrum and cosmic ray intensity
at $10^{17} - 10^{19}$ eV can be explained by galactic sources [1,2].
At present the most difficulties occur in the explanation of
EAS experimental data on anisotropy.

Is there really anisotropy? One of the arguments in
favour of anisotropy is the agreement of phases of the 1-st
harmonic on data of Yakutsk and Haverah Park EAS arrays [3]
(Fig.1). The common (Yakutsk and Haverah Park) chance proba-
bility of constancy of the 1-st harmonic phase at energy
range $5 \cdot 10^{17} < E_o < 2 \cdot 10^{19}$ eV is $10^{-4} \div 10^{-5}$. The next argument
in favour of anisotropy can be taken the presence of a gra-
dient in particle distribution on galactic latitude [4,5].
The chance probability of such a gradient on data of Yakutsk
and Haverah Park arrays in total is $10^{-5} \div 10^{-7}$ (Fig.2).

From the above it follows that cosmic ray anisotropy in
energy range $10^{18} - 10^{19}$ eV is real.

Experimental anisotropy. Because of small statistics the
experimentators on EAS data determine the anisotropy based on
event number on large solid angle $\Delta \mathcal{R}$ ($\Delta \delta_i \sim 90°$, $\Delta \alpha \sim 30 \div 60°$,
δ_i - declination, α - the right ascension). In [6] we
showed that anisotropy determined in such a way differs from
one δ determined by usual way on expected intensity:
$\delta = (I_{max} - I_{min})/(I_{max} + I_{min})$ where I - cosmic ray inten-
sity. Below we shall show it.

The particle number from the definite part of celestial
sphere is

$$n(\alpha, \delta_i) = \int K(\theta(t)) J(\alpha, \delta_i) \mathcal{R}(\theta(t), \Psi(t)) S(\theta(t)) dt,$$

where K - the probability of detection; $\mathcal{R}, S$ - the solid
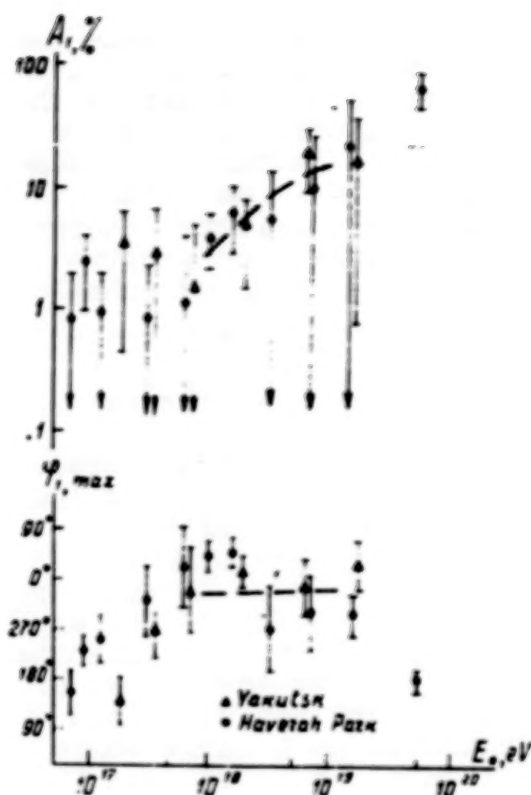
Fig.1. Amplitudes and
phases of the 1-st harmonic;
dashed line - the expected
values in the case of protons
from sources in the disc
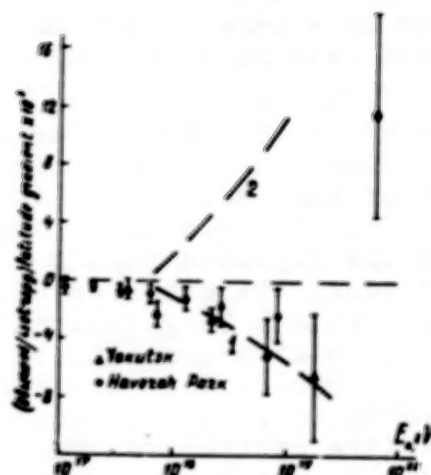
Fig.2. The gradient
$n_{obs.}/n_{isotr.}$ on galactic
latitude b. Dashed line
- the expected values in
the case of protons:
1 - Yakutsk, 2 - Sydney

angle and the effective area of the array; θ, φ - the zenith
and azimuthal angles, t - observation time. The number of
events on intervals of the right ascension is

$$n(\Delta d_i) = \int_{\Delta d_i} \int_{\delta} n(d, \delta_i) d d \, d\delta_i .$$

Then the anisotropy is

$$\delta^\circ = \left[n_{max}(\Delta d) - n_{min}(\Delta d) \right] \big/ \left[n_{max}(\Delta d) + n_{min}(\Delta d) \right] .$$

It is seen that anisotropy δ° determined on event number on
a large solid angle is not identical with anisotropy δ deter-
mined on intensity. Note that the some correction of the 1-st
harmonic amplitude in energy range $10^{18} - 2 \cdot 10^{19}$ eV (Fig.1)
can be made deviding it into $\cos b$ where b - the average
galactic latitude of the observed showers. The anisotropy
vector (Fig.1) is observed at the angle b. Similar idea
was supposed in [7] .

Galactic model. Discussed here anisotropy characteris-
tics at $E_0 > 10^{18}$ eV (the 1-st harmonic phases, a gradient

of particle distribution at positive latitudes) at quasi-
rectilinear motion of particles can be explained qualitative-
ly by sources distributed in the galactic disc (evidently the
maximum of particle arrival being from galactic plane where
the number of sources is large). At allowed on radiodata mag-
netic fields of disc (2-3 μG) and halo ($\leqslant 1$ μG) the
quasirectilinear motion is expected in the considered energy
range in a case of protons [1,2]. The observed on experi-
mental data ratio of showers equator-pole n(|b|< 30°)/n(|b|>

>30°) $\approx$ 2 about 10^{19} eV [5] can be also explained in the
case of protons by sources in galactic disc (in the first
approximation the particle number proportional to the ra-
dius of ball sectors of the region of sources).

Consider how these experimental data agree on amplitude
with the expected one from galactic sources. Calculating the
individual trajectories of antiprotons from the Earth in
sign-constant longitudinal magnetic field of the disc and
halo (the sign-constant field of the disc is considered to be
more probable, see, for instance, [8]) we estimated the exp-
ected anisotropy from sources distributed uniform in galactic
disc (the central sources can be excluded from the number of
possible ones [2]). The expected anisotropy was estimated
(Figs.1,3) by the expected particle number on a large solid
angle as in the case of experimental data (in detail see [6]).
The given anisotropy appears to be 2-3 times less than the
expected one determined on intensity, though they coincide
in phase. Note that the account of the inhomogeneous distri-
bution of sources in the disc changes weekly the estimated
anisotropy [6]. The observed ratio of showers equator-pole
on Yakutsk array data [5] (Fig.3) is
decreased due to the exposition time
of regions of sky [5].

We estimated the expected gradi-
ent of particles on galactic latitude
(Fig.2, see also [9]) from calcula-
ted lengths of trajectories in galac-
tic disc using formally the obtained
dependence of particle number upon
trajectory lengths [6] (in the case of
small solid angle, $\Delta b = 10°$, $\Delta l \sim 120°$,
we can not strictly use the this de-
pendence).

On χ^2-criterium we compared the
observed event number on right ascen-
sion [5] with the expected one in the
case of protons from sources in the
disc. We supposed that the observed
number of events is a sum of aniso-
tropic galactic (G-portion) and iso-
tropic extragalactic cosmic ray com-
ponents. In the Table are shown G at
which χ^2 is minimum, in brackets -
upper limits of G.
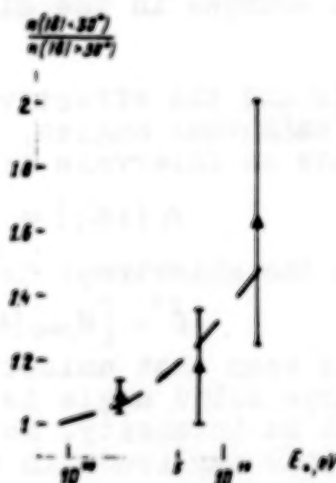
Fig.3. The ratio of
showers equator-pole.
Dashed line - expected
in the case of pro-
tons from sources in
the disc

E_0, eV	Number of showers	G,%
$2,1 \cdot 10^{18}$	3147	80(100)
$6,7 \cdot 10^{18}$	256	100(100)
$1,7 \cdot 10^{19}$	115	100(100)

Table

On results of comparison of the observed and expect anisotropies on amplitude and phase of the 1-st harmonic, on ratio of the number of showers equator-pole, on χ^2-criterium the particles with energies up to 10^{19} eV can be considered of galactic origin.

Our detailed calculations on galactic model show [2,6] that at energies above 10^{18} eV the maximum of particle arrival from the high galactic latitudes is not expected. The observed excess of particles from the high latitudes [4,5,7,10] at energies $E_0 > 2 \cdot 10^{19}$ eV, to be more accurate, from direction of centre of the Local supercluster to be probably caused by extragalactic sources.

Conclusion. The particles with energies up to 10^{19} eV are of galactic origin and above $2 \cdot 10^{19}$ eV are rather of extragalactic origin.

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ABUNDANCE OF LOW ENERGY (50-150 MeV)
ANTIPROTONS IN COSMIC RAYS **N85-34092**

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ABSTRACT

We present the progress of our nuclear emulsion
experiment to determine on abundance of low energy
antiprotons in cosmic rays. We have not detected
any so far and obtain an upper limit of $\bar{p}/p \leq 4 \times 10^{-4}$
in the energy range 50-150 MeV.

During the last International Conference on Cosmic Rays
at Bangalore, we[1] reported preliminary results of an experi-
ment to determine the abundance of low energy antiprotons in
cosmic rays. We are using a nuclear emulsion stack of 200
Ilford G5 emulsion pellicles exposed on July 3, 1972 at Fort
Churchill, Canada for 13h 45m at a depth of 1.7 $g.cm^{-2}$ of
residual atmosphere. We scanned at a depth of mostly 2 cms
from the top edge, for nuclear interactions containing one
high energy track and then followed all tracks in the upper
hemisphere towards the edge of the entry. This will pick
out interactions produced by a particle coming from outside
the stack. The signature of a low energy anti-proton is a
track corresponding to a slow particle (<200 MeV) of protonic
mass and producing an interaction with a visible energy re-
lease more than the kinetic energy of the incoming proton[2].

In the previous ICRC we had reported five candidates.
These were obtained by making grain density measurements
along the track, which indicated the direction of motion of
the particle producing the track, i.e. whether the particle

is coming into the interaction or produced in the interaction and going away from the interaction. None of the candidates stopped in the emulsion at the point of interaction. We have now scanned a total volume of 7.8 cm^{-3} of emulsion. A total of about 19,590 interactions were looked at and 10,169 tracks were followed towards the top of the stack. Out of these 288 tracks left the stack at the top and grain density measurements were carried out on them. Those that showed that they are proceeding towards the interaction are called candidates for $\bar{p}$ and were subjected to blob-gap measurements in all pellicles through which they pass. We have made extensive grain density and blob-gap measurements on relativistic alpha tracks in various regions of the stack to determine variations of the sensitivity of the emulsion in a single pellicle as well as from pellicle to pellicle. We used stopping protons and electron pairs to obtain the calibration curves for ionization versus range.

With the above effort, we found that the previous candidates are not anti-protons. We also found another 15 candidates, which also did not turn out to be antiprotons. We have calculated the gathering power of our volume to be 2.38×10^3 m^2.sr.s.MeV yielding as an upper limit to $\bar{p}$ flux of $\sim 4 \times 10^{-4}$ m^{-2}.s^{-1}.sr^{-1}.MeV^{-1} in the energy range 50-150 MeV. This flux limit is to be compared to the flux of $(1.7 \pm 0.5) \times 10^{-4}$ m^{-2}. sr^{-1}. s^{-1}. MeV^{-1} obtained by Buffington et al.[3]; however the flux obtained by Buffington et al. is in the energy range 130-320 MeV. The upper limit to the $\bar{p}/p$ ratio in the energy range 50-150 MeV is obtained using the proton flux in this energy range of 0.96 ± 0.07 m^{-2}. s^{-1}. sr^{-1} MeV^{-1} obtained* from IMP-6 satellite on this date, and is 4.3×10^{-4} (1σ).

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* We are thankful to Dr. T. von Rosenvinge for this information.

In the last ICRC we reported an event which we interpreted as an anti-triton event on the basis of grain density measurements. Since then we have made blob gap measurements and multiple scattering measurements on the track in all the pellicles through which it passes. After taking into account the plate to plate variations, we found that the ionization measurements made the identification of the incoming track between t and He^3 ambiguous; perhaps more consistent with He^3 nucleus (Fig. 1). In Fig. 2 we show the plot of normalised ionization parameter obtained from blob-gap measurements, versus the multiple scattering parameter for 100μ cell length. (The parameter for 100μ is obtained from values obtained from higher cell lengths and the usual third difference method to remove distortion effects). The curves for H^3 and He^3 are shown. Here again we do not find convincing evidence that the incoming track is a triton, eventhough the measurements do not fit well with a He^3 curve. Therefore, we do not believe the track to be due to an anti-triton.

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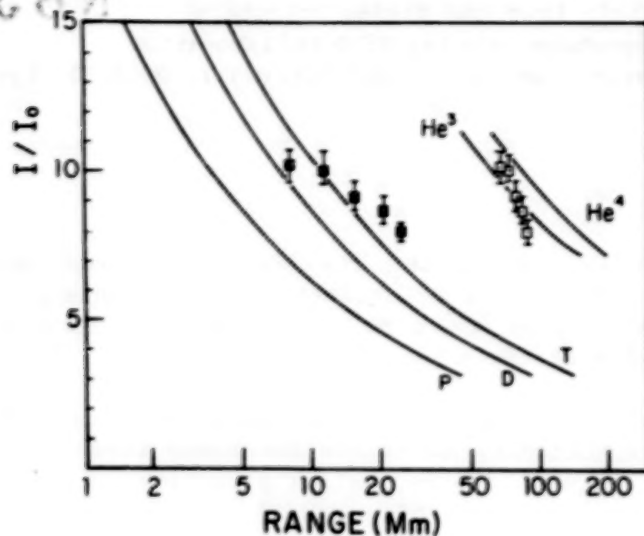
Fig. 1. Normalised ionisation parameter I/I_0 obtained from blob-gap measurements versus residual range. The curves for protons (P) and He^4 are obtained from calibration tracks. The measurements of the candidate track are plotted once on the triton curve and once on He^3 curve to examine the fits.
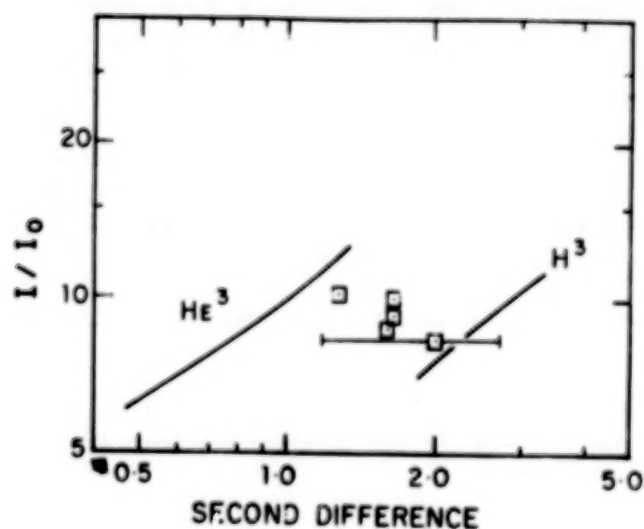
Fig. 2. Normalised ionisation parameter I/I_0 obtained from blob-gap measurements versus scattering parameter. The measured values for the candidate track are plotted; typical error is shown.

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SEARCH FOR HEAVY ANTINUCLEI IN THE COSMIC RADIATION

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Introduction

The cosmic radiation is one of the few channels through which the existence of significant amounts of antimatter in the Universe may be demonstrated. Such a finding would be of fundamental importance for cosmology as well as for particle physics.

The data from the Danish-French Cosmic Ray Spectrometer on the HEAO-3 satellite offers an opportunity to search for heavy antinuclei, since all the relevant parameters (charge, velocity, arrival direction, and satellite position at the time of arrival) are measured for each recorded nucleus.

Instrumentation and initial data selection

The HEAO-3 instrument is described in detail in (3). The charge and velocity of each particle is determined from the signals produced in a stack of five Cerenkov counters.

The consistency of the signals are used to check for particles undergoing nuclear interactions while traversing the instrument. For this investigation, however, the consistency requirements have been relaxed somewhat from the values used generally, in order not to reject antinuclei, which are expected to yield signals differing slightly from those of their positive counterparts.

The particle velocity is determined from a fit to the Cerenkov signals. We use a routine which determines not only the best fit velocity, but also the lower and upper bounds for a velocity interval outside which the true values should only lie in one case out of 10^5.

Particles with inconsistent values of the velocity signals have been rejected.

The present analysis is limited to elements heavier than fluorine since the reliability of the time-of-flight system has been found to degrade somewhat for lighter elements.

Pilot runs showed that the number of particles with zenith angles less than 90° which could be assigned a unique charge is quite small. Consequently we restrict the data base to particles with zenith angles greater than 90°.

Trajectory tracings

Before beginning the trajectory tracings the acceptable velocity range mentioned above is converted to a rigidity interval by using a very wide range of possible isotopic masses for each element. This procedure

takes into account the possibility that a short lived fragment produced in the atmosphere may follow a different trajectory than the ones available to the stable isotopes.

The helix-method (4) is used for the trajectory tracings. The magnetic field model used is a 14. order model based on MAGSAT data (5). For each rigidity value it is checked if any of the two possible charge signs corresponds to an acceptable arrival situation. Dependent on the outcome of the tracings the particles are divided into four classes:

1) Both charge signs are possible. This class contains all events for which at least one positive rigidity and at least one negative rigidity are acceptable.

2) Only a positive sign is possible, i.e., particles for which at least one positive rigidity is acceptable and none of the negative rigidities are acceptable.

3) Only a negative sign is possible, i.e., all positive rigidities forbidden, but at least one negative is allowed.

4) Neither sign is allowed, all positive as well as negative rigidities are forbidden.

A very conservative criterion for classifying a rigidity as "forbidden" has been used. It is demanded that the corresponding trajectory intersects the solid Earth within a trajectory length of one Earth radius from the satellite position.

In order to allow for some error in the determination of the particle arrival directions, any particle which is initially in class 2, 3 or 4 is recalculated using a zenith angle diminished by 2 degrees relative to the measured value.

Results

Of the initial data set about 25% or 34070 events are classified as positive only, 15 events are negative only (antiparticle candidates) and 10 events are impossible regardless of the sign assumed. The rest, 103266 events, are consistent with either charge sign.

Details on the 25 particles of classes 3 and 4 can be found in tables 1 and 2.

Inspection of these 25 events reveals that 7 antiparticle candidates and 2 impossibles were all recorded on one single day (Nov. 11, 1979). The total set comprises data from over 400 days. We have found no satisfactory explanation for this burst of unusual trajectories. There were no signs of instrument or satellite malfunctions. A Forbush decrease occurred on this day, but we see no particular reson to connect the two events. The geomagnetic activity index was between 1 and 2+. We have noted that 8 of the 9 unusual events were recorded in the vincinity of the Sourth Atlantic Anomaly. The instrument was switched off during the passages through the Anomaly and the 8 events occurred in the first few minutes after switch on. The connection

between the switching of the experiment and the peculiar events is not obvious, however, because in the total data set there are several thousand such passages without irregularities. We have therefore decided to reject all events (of all classes) recorded on this day from this work.

The remaining 8 impossible events indicate the level of background for the antiparticle search. This background may be due to inadequacies of the measured data (charge, velocity, and arrival direction for the particles) or it may arise due to inadequacies of the magnetic field model. The MAGSAT model does not describe local crust related magnetic anomalies and does not take into account magnetic disturbances which might exist at the specific time of our particle recordings.

When analyzing the geographic distribution of the remaining "impossibles", it appears that the problem lies with the magnetic field data because these particles have preferentially been detected at low geomagnetic cut-off values where magnetospheric disturbances have the largest effect. We have therefore investigated the effect of excluding data obtained at locations with geomagnetic L-values greater than 1.5. It turns out that most of the "particle" candidates remain in this selection whereas all the "antiparticle" candidates and all but one of the "impossibles" are gone. This last "impossible" event may be reasonably attributed to the uncertainty of the time-of-flight imformation. In fact, an independent analysis leads us to suspect a residual contamination at the 10^{-4} level for the time-of-flight system. We also note that all but one of the Nov. 11 events have L-values greater than 1.5.

Conclusion

Using the 22676 "positive only" events in the data selection corresponding to $L \leq 1.5$ as a measure of our "exposure factor" to heavy antinuclei and noting that no corresponding antinuclei were found we can give an upper limit (95% confidence) to the ratio of antinuclei to nuclei as 1.4×10^{-4} for particles with $|Z| > 9$. In table 3 we compare the upper limit resulting from this work with previous results of searches for heavy antimatter in the cosmic radiation. It is seen that, if one regards only antiparticles heavier than fluorine, then the present result represents a reduced upper limit over previous data. When taken together, all the available experiment data now push the upper limit for the ratio of antiparticles to particles well below 10^{-4}.

As a final remark we may stress that we have found no satisfactory explanation for the 9 unusual particle tracks seen on November 11, 1979. We would appreciate being informed of other geophysical "curiosities" which might have been observed on this date.

Acknowledgements

N85-34004

TABLE 1   Antiparticle candidates

Date	GMT	Lat.	Long.	L-value	Zen.	Az.	Z	p GeV/c	4.3 σ range
791111	07 59	-43.3°	32.1°	2.51	128°	20°	10	4.13	3.74 - 4.89
791111	07 59	-43.3	32.3	2.51	123	44	14	1.58	1.52 - 1.65
791111	08 00	-43.5	37.0	2.52	135	18	13	4.66	4.19 - 5.54
791111	08 01	-43.6	39.7	2.52	107	29	19	8.02	7.40 - 9.31
791111	09 37	-43.0	27.3	2.49	119	36	14	2.16	1.98 - 2.45
791111	09 37	-42.8	28.9	2.49	129	15	14	5.38	4.66 - 6.41
791111	09 38	-42.4	31.6	2.49	122	36	14	2.11	1.94 - 2.35
791215	14 46	-43.6	74.8	3.0	105	138	10	1.17	1.14 - 1.19
800129	17 18	-38.0	133.4	2.5	109	79	13	7.22	6.70 - 8.22
800205	09 08	-43.4	-175.8	2.4	130	-63	12	2.14	1.94 - 2.48
800206	00 04	41.8	148.9	1.6	95	55	12	6.28	5.27 - 6.70
800415	02 20	-43.6	-36.4	1.63	109	46	10	3.09	2.97 - 3.28
800715	20 13	-36.8	61.2	2.2	114	52	18	7.15	6.73 - 7.90
801025	09 35	-36.5	-171.7	1.75	99	123	10	8.73	7.44 - 12.94
801031	13 38	-41.2	102.0	3.0	107	116	12	8.81	7.66 - 11.94

TABLE 2   "Impossible particles"

Date	GMT	Lat.	Long.	L-value	Zen.	Az.	Z	p GeV/c	range
790930	20 57	-42.8°	104.8°	3.3	135°	-75°	12	4.30	3.89 - 5.02
791005	18 06	41.8	-71.3	3.1	119	-48	13	1.21	1.20 - 1.22
791017	17 08	-43.3	72.2	3.0	134	86	13	1.97	1.82 - 2.21
791111	10 05	16.2	116.3	1.0	146	114	16	56.36	15.4 - ∞
791111	11 22	-25.9	48.2	1.6	109	171	12	6.73	6.34 - 7.44
791208	21 04	-43.5	18.2	2.3	168	70	10	1.28	1.26 - 1.32
800628	17 08	-43.6	-176.0	2.4	147	-107	20	5.43	4.87 - 6.31
800823	00 50	-43.5	57.6	2.4	152	-54	14	2.68	2.34 - 2.97
800912	05 19	35.6	2.6	1.5	144	-79	10	16.36	10.13 - ∞
801105	06 32	38.7	-12.3	1.8	129	14	20	20.07	11.42 - ∞

TABLE 3   Searches for antinuclei

		95% confidence upper limit
Badhwar et al (1978)	Z = 2	1.7×10^{-4}
Smoot et al (1975)	Z > 2	0.8×10^{-4}
Present work	Z > 9	1.4×10^{-4}

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PROPAGATION AND SECONDARY PRODUCTION OF LOW ENERGY ANTIPROTONS IN THE ATMOSPHERE

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1. Introduction. Current theories, in which the observed antiproton component is attributed strictly to secondary production in high energy inelastic collisions of protons with the interstellar medium or the atmosphere, apparently fail to explain the relatively high $\bar{p}$ vertical intensities measured at mountain and balloon altitudes. Therefore, a more careful calculation of the theoretical secondary intensity spectra is required before more exotic sources for these excess $\bar{p}$'s can be explored.

In this paper, we have used a one-dimensional diffusion equation (valid if $\theta_{lab} \lesssim 20^{\circ}$ down to sea level) to calculate the expected vertical intensity of $\bar{p}$'s due only to secondary production in the atmosphere; any assumed primary $\bar{p}$ spectrum can also be included. Two adjustable parameters, the inelasticity and charge exchange in nucleon-nucleus collisions, were included in our algorithm. In order to obtain an independent estimate of their values, we first calculated the proton vertical intensities in the atmosphere, adjusting the parameters until our curves fit the experimental proton data, and then assumed that these values were identical in antinucleon-nucleus collisions.

2. Results. Our calculations followed a method suggested to us by T. K. Gaisser in which the atmosphere was divided into "slabs" of equal thickness Δx; slabs of 1 g/cm^2 were used. In calculating the differential proton intensities, a primary proton spectrum of the form[1] $j_p = 2(E + 2.15)^{-2.75}$ cm^{-2}-s^{-1}-sr^{-1}-GeV^{-1}, where E is the proton kinetic energy in GeV, was assumed. Protons and neutrons from higher Z nuclei were assumed to have the same spectral shape, and all protons and nuclei whose momenta were less than the vertical cutoff rigidity were excluded. Then, working from the top of the atmosphere down to sea level, the proton intensity of the i + 1 slab was calculated using the equations $n(i + 1) = n(i) + (dn(E)/dx)\Delta x$ and

$$\frac{dn_p(E)}{dx} = - \frac{n_p(E)}{\lambda_{inel}^{air}} + (\frac{dE}{dx})\frac{\Delta n_p}{\Delta E} + \int_{E_0=E}^{\infty} \frac{1}{\lambda_{inel}^{air}} \frac{dN(E,E_0)}{dE} [(1-\alpha)n_p(E_0) + \alpha n_n(E_0)]dE_0 , \quad (1)$$

with a similar equation [without the ionization loss[2] term $(dE/dx)(\Delta n_p/\Delta E)$] for the neutron intensity, n_n. All of the values of n on the right-hand side are the values from the slab i above. λ_{inel}^{air} is the inelastic mean-free path of proton-air nuclei collisions, scaled from p-^{12}C data.[3,4] The last term in the equation above adds in the protons gained from inelastic collisions of higher energy protons with air nuclei, with $dN(E,E_0)/dE$ defined as the probability of a proton with initial energy E_0 possessing energy E after collision. A uniform probability distribution ranging from 0 to ϵE_0 for $dN(E,E_0)/dE$, with average elasticity $\epsilon/2$, was assumed. ϵ and the probability α of charge exchange were our adjustable parameters. With the values $\alpha = 0.333$ and $\epsilon = 0.9$, our computed proton intensities matched the experimental data quite well (see Fig. 1). We then used these values for ϵ and α in our antiproton intensity calculations.
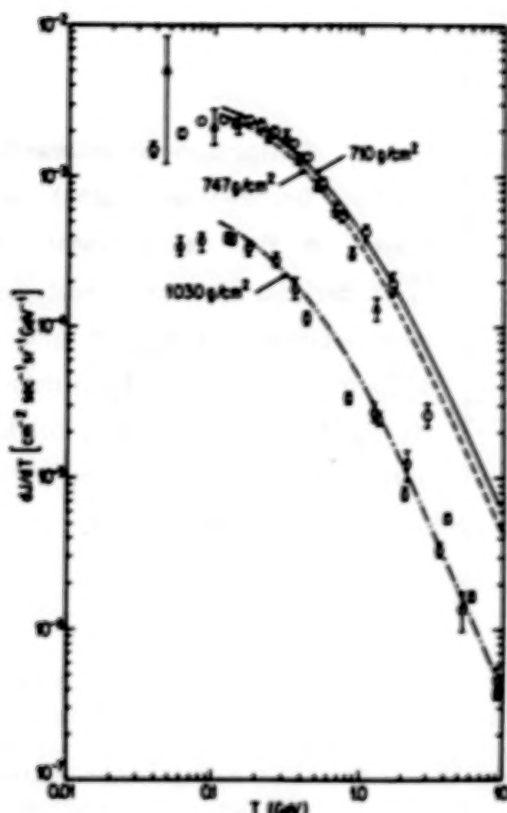
Fig. 1.   The curves show the calculated results for vertical proton intensities at 710, 747, and 1030 g/cm^2 depth.   The data is a compilation by Barber et al., Ref. 14.

Using the same method, the antiproton intensity due only to secondary production was calculated with equations analogous to Eq. (1), but with the term,

$$\int_{E_0=E}^{\infty} \frac{1}{\lambda_{inel}^{air}} \frac{1}{\sigma_{inel}^{air}} \frac{d\sigma_{\bar{p}}^{air}(E,E_0)}{dE} n_{nucleon}(E_0)dE_0 \quad ,$$

added on the right side for the production spectrum of $\bar{p}$'s in proton-air collisions, which is taken from a parameterization of Tan and Ng,[5] attenuated with an attenuation length of 122 g/cm^2 as depth increases.   The form of dE/dx and $dN(E,E_0)/dE$ were the same as used in the proton calculations. λ_R^{air}, the $\bar{p}$ mean-free path in air for annihilation and inelastic scattering, was estimated by scaling a power-law fit to $\bar{p}$-^{12}C reaction cross sections from data compiled by G. Bruge and provided to us by J. C. Peng, LAMPF; the result is shown in Fig. 2, curve d, along with another estimate,[7] curve e.   Three different forms of λ_{inel}^{air}, the antiproton mean-free path in air for inelastic, non-annihilation collisions, were tried, as shown in Fig. 2.   In version c, λ_{inel}^{air} was assumed to be equal to λ_{inel}^{air} for protons.   A curve from Szabelski and Wolfendale[7] was used in version b.   Finally, in version a, we attempted a realistic estimate for λ_{inel}^{air} by assuming that λ_{inel}^{air}/ $\lambda_{annih}^{air} = \sigma_{annih}(\bar{p}p)/\sigma_{inel}(\bar{p}p)$.   Since there is little data available on $\sigma_{inel}(\bar{p}p)$ [non-annihilation], we assumed that it is the same as the pp inelastic cross section.[8]   Below 0.5 GeV, λ_{inel}^{air} depends entirely on quasi-elastic $\bar{p}$-nucleon scattering; for our realistic estimate shown in curve a, the quasi-elastic scattering was taken to be 1/10 as probable as for the p-nucleon case, based upon special Monte Carlo runs using ISABEL INC for $\bar{p}$-^{12}C inelastic scattering at 180 and 400 MeV[9] arranged for us by P. L. McGanghey at Los Alamos.
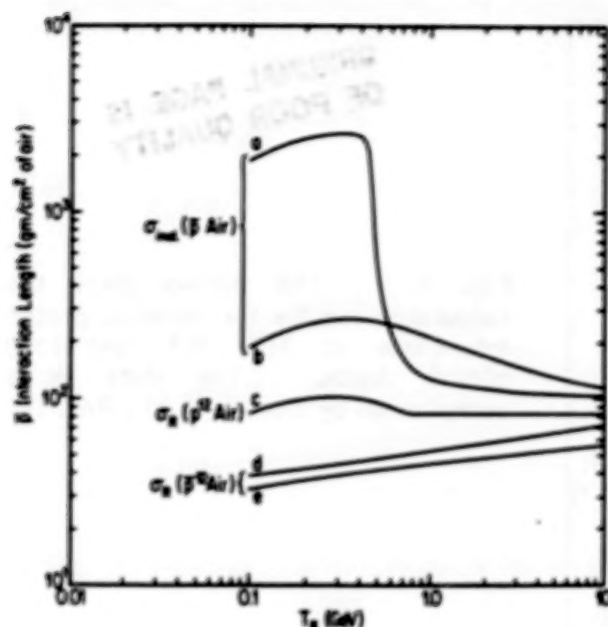
Fig. 2. Antiproton-air interaction lengths (mean-free paths) employed in the calculations: (a) λ_{inel}^{air} derived from our most realistic estimate of $\sigma_{inel}(\bar{p}\text{-air})$; (b) λ_{inel}^{air} from Ref. 7; (c) λ_{inel}^{air} derived if $\sigma_{inel}(\bar{p}\text{-air}) = \sigma_R(p\text{-air})$; (d) λ_R^{air} derived from our fit to $\sigma_R(\bar{p}\text{-}^{12}C)$ data; (e) λ_R^{air} from Ref. 7.

The results of our antiproton calculations, along with experimental data for the $\bar{p}$ vertical intensities at mountain altitudes, are shown in Fig. 3. At mountain altitude, both curves a and c are consistent with observations by the Arizona group,[10] although we feel that the comparison with curve a, our most realistic estimate, is the more significant one. At balloon altitudes, our secondary $\bar{p}$ intensity estimates are an order of magnitude below the intensities reported by Buffington et al.[11] and Golden et al.[12]
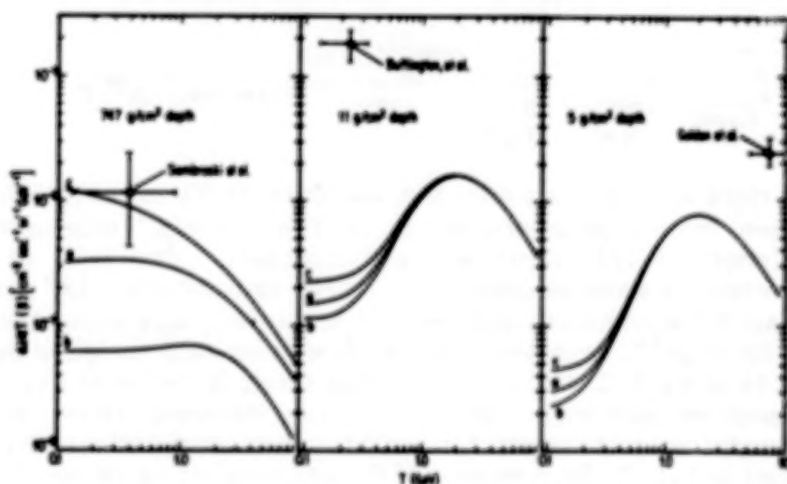
Fig. 3. The curves show calculated antiproton intensities produced by atmospheric interactions at 747 g/cm^2, 11 g/cm^2, and 5 g/cm^2 depth. The data points are taken from Refs. 10, 11, and 12. The designations (a), (b), and (c) correspond to utilizing curves (a,d), (b,e), and (c,d), respectively, from Fig. 2.

These results assume that there is no primary $\bar{p}$ spectrum. We then added to version "a" a primary $\bar{p}$ spectrum normalized by passing through the point of Golden et al.[12] at 8.5 GeV of the form $j_{\bar{p}}=(2.4\times10^{-6})[(E+0.94)/9.44]^{-\gamma}$. If $\gamma=2.75$ as for the proton spectrum, then the resultant low energy spectrum at mountain altitude (747 g/cm^2) was 2.0% greater than the purely secondary $\bar{p}$ spectrum; with $\gamma=2.1$ as suggested by Stecker and Wolfendale,[13] the primary $\bar{p}$ contribution at mountain altitude increases to 4.8%. Then γ was adjusted until the calculated low energy $\bar{p}$ intensity at 747 g/cm^2, due to the primaries, equaled the difference between the data from Bowen et al.[10] and the calculated result for purely secondary $\bar{p}$ spectrum [Fig. 3(747 g/cm^2), curve a]. A rather flat spectrum, $\gamma=0.95$, is required. We also determined the most probable energy of the primary antiprotons contributing to the low energy $\bar{p}$'s at 747 g/cm^2: for $\gamma=2.1$, it was 30 GeV; for $\gamma=1.5$, 240 GeV; for $\gamma=0.9$, 3800 GeV. Obviously, more data on the antiproton intensities at high altitudes, as well as additional data on $\bar{p}$ cross sections, are needed before making an analysis with fewer approximations.

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SECONDARY ANTIPROTON PRODUCTION IN RELATIVISTIC PLASMAS

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I. Introduction. We investigate the possibility that the reported excess low energy antiproton component of the cosmic radiation results from proton-proton (p-p) interactions in relativistic plasmas. Because of both target and projectile motion in such plasmas, the antiproton production threshold in the frame of the plasma is much lower than the threshold of antiproton production in cosmic ray interactions with ambient matter. The spectrum of the resultant antiprotons therefore extends to much lower energy than in the cosmic ray case.

We calculate the antiproton spectrum for relativistic thermal plasmas and estimate the spectrum for relativistic nonthermal plasmas. As possible production sites, we consider matter accreting onto compact objects located in the galaxy. Possible overproduction of γ-rays from associated π° production can be avoided if the site is optically thick to the photons but not to the antiprotons. A possible scenario involves a sufficiently large photon density that the π° γ-rays are absorbed by γ-γ pair production. Escape of the antiprotons to the interstellar medium can be mediated by antineutron production.

II. Observations and Constraints on Secondary Production Models.

Golden et al. (1979) have reported an antiproton to proton ($\bar{p}/p$) ratio of $5.2(\pm1.5)\times10^{-4}$ in the cosmic radiation in the energy range 4.7-11.6 GeV. Bogomolov et al. (1979), on the basis of only two events, report a $\bar{p}/p$ ratio of $6(\pm4)\times10^{-4}$ at energies between 2 and 5 GeV. Buffington et al. (1981) report a $\bar{p}/p$ ratio of $2.2(\pm0.6)\times10^{-4}$ between 130 and 320 MeV, and also determine that the antihelium to helium ratio $\bar{a}/a < 2.2\times10^{-5}$ in the energy range 130-370 MeV/nucleon. Upper limits on prior antinucleus searches can also be found in this paper.

As is well known, the simple "leaky box" model of cosmic ray propagation predicts a $\bar{p}/p$ ratio smaller by a factor of 3-5 than the values measured in the Golden and Bogomolov experiments. Because of the kinematic cutoff associated with the high $\bar{p}$ production threshold in p-p collisions when one of the protons is at rest, the $\bar{p}/p$ ratio predicted by this model is some two orders of magnitude lower than the value reported by Buffington et al., even after the effects of solar modulation are taken into account (Tan and Ng 1983a). The low $\bar{a}/a$ ratio, in comparison with the $\bar{p}/p$ ratios, suggests a secondary origin of the $\bar{p}$, although primary cosmic ray antiproton theories, with subsequent breakdown of the A > 1 antinuclei, have been proposed (e.g., Stecker et al. 1983).

Theories of secondary $\bar{p}$ production in p-p collisions in the galaxy are constrained by the observed galactic gamma-ray luminosity. The observed antiproton flux $\phi_{\bar{p}}$ (E) implies a total galactic $\bar{p}$ production rate

$$Q(\bar{p}) \sim \frac{4 V}{c} \int_0^\infty dE \frac{\phi_{\bar{p}}(E)}{\beta \cdot \tau(E)} \sim (3.5 \times 10^{-14} V/\tau) \ \bar{p}/sec,$$

where V is the galactic confinement volume and τ is the average galactic $\bar{p}$ residence time. Taking $V \sim \pi (15 \text{ kpc})^2 (1 \text{ kpc}) \sim 1.2 \times 10^{67} \text{ cm}^3$ and $\tau \sim 10^7$ yrs gives $Q(\bar{p}) \sim 2.1 \times 10^{39} \ \bar{p}/sec$. If the production of a secondary $\bar{p}$ is accompanied by the production of $\langle n \rangle \ \pi^\circ$-decay gamma rays, the resultant γ-ray luminosity of the galaxy $Q(\gamma) \sim \langle n \rangle Q(\bar{p})$. In the case of the production of >100 MeV photons in cosmic ray interactions, $\langle n \rangle_{cr} \sim 2.7 \times 10^3$, from the calculations of Stephens and Badhwar (1981) and Tan and Ng (1983a). If the $\bar{p}$ in the cosmic radiation are entirely cosmic ray secondaries, the > 100 MeV luminosity of the galaxy should therefore be at least $5.7 \times 10^{42} \ \gamma/sec$, in contrast to the measured value of $\sim 2.5 \times 10^{42} \ \gamma/sec$ from the work of Bloemen et al. (1984). This latter number is an upper limit, since it includes a significant contribution from bremsstrahlung and inverse Compton γ-rays.

Various models have been designed to either increase the $\bar{p}$ lifetime τ, incorporate additional $\bar{p}$ sources, or conceal the π° γ-rays. Although the integral production rate of $\bar{p}$ can then be made to agree with observations, most models still fail to predict a substantial low energy $\bar{p}$ flux because of the low energy cutoff that results from secondary interactions with stationary targets, in disagreement with the experiment of Buffington et al. (1981). Models that provide deceleration of the $\bar{p}$
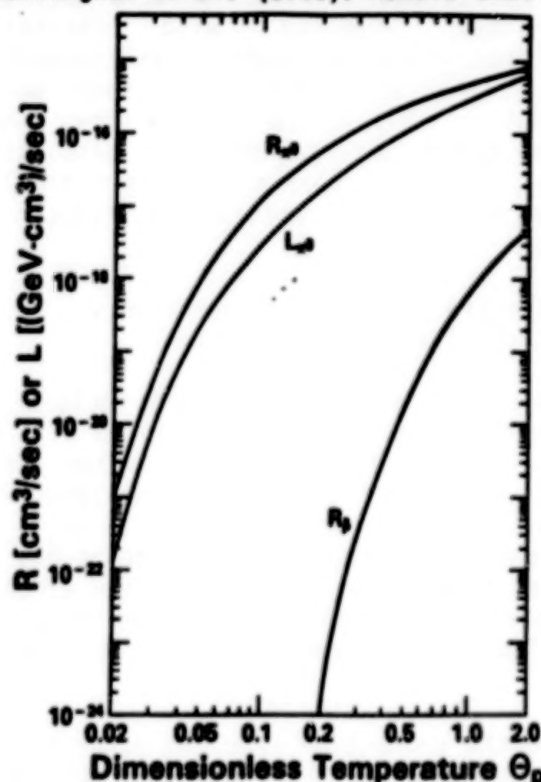
after production or require that the Solar System occupies a special position in the galaxy have also been proposed (Stephens and Mauger 1984; Tan and Ng 1983b).

III. Secondary Discrete Source Model. We examine the possibilities that the low energy antiprotons observed in the cosmic radiation are produced through secondary p-p interactions in relativistic plasmas in the vicinity of a neutron star or black hole. At proton temperatures $\theta_p = kT/m_p c^2 \geq 0.2$ ($\theta_p = 1$ corresponds to $\sim 10^{13}$ K), a significant number of secondary $\bar{p}$ can be produced. We have calculated the rate coefficients and production spectra (Weaver 1976; Dermer 1984) for secondary $\bar{p}$ using the

Fig. 1. The rate coefficients for secondary π° and $\bar{p}$ production from p-p collisions in a relativistic plasma at temperature $\theta_p = kT/m_p c^2$. Also shown is the π° luminosity coefficient giving the total energy in secondary π° γ-rays produced at temperature θ_p.

Fig. 2. Secondary p̄ production spectra at various temperatures
$\theta_p = kT/m_p c^2$ are given as a function of kinetic energy E.
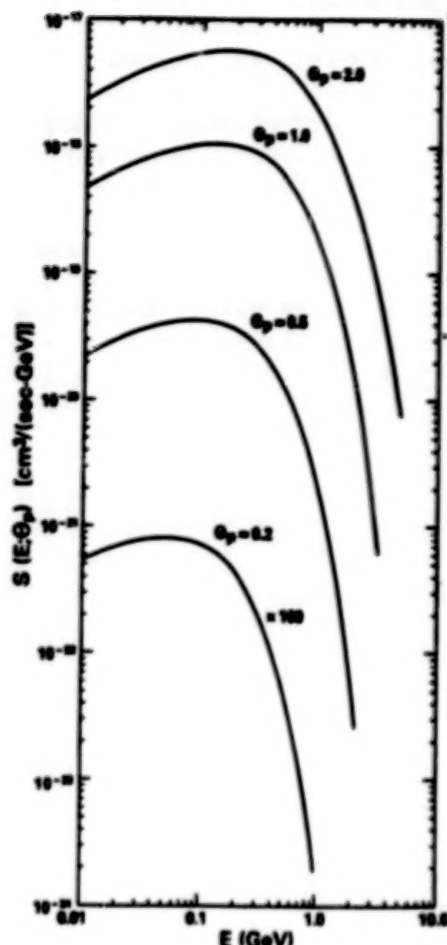
invariant cross section of Tan and Ng (1982) and the results are shown in Figs. 1 and 2. We have also calculated the rate and luminosity coefficients from secondary $\pi^°$ production data. From Fig. 1 we find that the efficiency for p̄ production compared to $\pi^°$ production is greater than in the cosmic ray case for $\theta_p \gtrsim 0.5$, so the total $\pi^°$-decay γ-ray luminosity will not exceed limits implied by γ-ray observations of the galaxy. In addition, a number of absorption processes likely to occur near compact objects, such as photon-photon or magnetic pair production, can further reduce the $\pi^°$ γ-ray luminosity.

The p̄ spectra shown in Fig.2 for a variety of temperatures extend to low energies without the appearance of the kinematic cutoff found in the cosmic ray problem. The spectra peak at higher energies with increasing temperature, and exhibit an exponential decline above the peak temperature. But in all cases a very low energy secondary p̄ component is calculated, which could possibly explain the low energy p̄ observation of Buffington et al. (1981).

IV. Discussion. Possible production sites of the p̄'s include the galactic bulge binary X-ray sources or the objects associated with the γ-ray point sources (e.g. Cyg X-3). Models for disk accretion (Eilek 1980) and spherical accretion incorporating shocks (Meszaros and Ostriker 1983) could yield proton temperatures as high as $\theta_p \sim 1$. Although the establishment of a thermal distribution of protons may not be possible at these temperatures, this assumption affords the simplest calculations. Preliminary estimates employing nonthermal proton spectra in relativistic plasmas suggest low energy p̄ spectra similar in form to the results of Fig. 2.

Transport of the secondary p̄ from the production site can occur because antineutrons n̄, produced in equal numbers as the p̄ (Gaisser and Maurer 1973), are not confined by the ambient plasma magnetic field. The n̄ will escape to the interstellar medium and subsequently decay into p̄ (the calculations of Figs. 1 and 2 refer only to these particles). Because of the finite lifetime of the n̄, an upper limit can be placed on the mass of black holes that serve as production sites for the p̄. Requiring that the marginally relativistic n̄ escape to ~ 10 Schwarzschild

radii implies a maximum black hole mass of $<10^7 M_0$. Past activity around such a massive black hole at the Galactic Center could have produced the antiprotons without a large contemporaneous gamma emission. A detailed treatment of $\bar{p}$ production in a relativistic plasma must also include distortions of the emergent $\bar{n}$ and γ-ray spectrum due to the intense gravitational field of the compact object, and possible reacceleration of the source spectrum in the galactic environment.

V. Conclusions. We have presented a model that can produce low energy antiprotons through secondary p-p interactions in relativistic plasmas. Such a model is in agreement with the observation of low energy antiprotons in the cosmic radiation and the observed γ-ray luminosity of the galaxy. Moreover, it agrees with the present lack of observations of antinuclei in the cosmic radiation, whose formation by secondary production processes is entirely negligible.

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THE FLUX OF SECONDARY ANTI-DEUTERONS AND ANTIHELIUM PRODUCED IN THE INTERSTELLAR MEDIUM

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Abstract

Several measurements have been performed to find antiprotons in the primary cosmic radiation. Because it is difficult to get completely separated secondary produced antiprotons from primary ones, calculations based on accelerator results have been performed for the flux of secondary produced antideuterons and antihelium.

1. Introduction. Antiprotons in the primary cosmic radiation have been detected in the kinetic energy range between 130 MeV and 11.6 GeV by different groups and different methods (Golden et al., 1979; Bogomolov et al., 1979; Buffington et al., 1981).
It was not conclusively possible to demonstrate if there was a contribution of primary antiprotons. Since cross-sections for secondary produced $\bar{d}$, $^3\overline{He}$ and $^4\overline{He}$ are some orders of magnitude lower than for $\bar{p}$ the secondary background would be negligible.

2. Methods. Using the data for the production of $\bar{d}$ in pp-collisions at $\sqrt{s} = 45$ GeV and $\sqrt{s} = 53$ GeV and for the production of $^3\overline{He}$ at $\sqrt{s} = 19.4$ GeV (Albrow et al., 1975; Gibson et al., 1978; Armitage et al., 1979; Bussière et al., 1980) the following fits for the invariant cross-sections for the production of $\bar{d}$ and $^3\overline{He}$ were obtained:

$$\left(E\frac{d^3\sigma}{dp^3}\right)_{\bar{d}} = 4\,(1-x_R)^{16}\,\exp\,(-2.62p_T)\,\times\,10^{-3}\left[\text{mbc}^3/(\text{GeV})^2\right],$$

$$\left(E\frac{d^3\sigma}{dp^3}\right)_{3\overline{He}} = (1 - x_R)^{24} \exp(-2p_T) \times 10^{-7} \left[mbc^3/ (GeV)^2\right],$$

$x_R = \frac{E^*}{E^*_{max}}$: radial scaling variable;

E^*: energy of the antiparticle in the center-of-mass system;
E^*_{max} : maximum energy of the antiparticle in the center-of-mass system;

p_T : transverse momentum.

The measured invariant cross-sections, which were used for the fits, have a statistical error of about 30 %.

With a mass dependence for the invariant cross-section (Bussière et al., 1980) the fit for the invariant cross-section of $^4\overline{He}$ was obtained:

$$\left(E\frac{d^3\sigma}{dp^3}\right)_{4\overline{He}} = (1 - x_R)^{32} \exp(-2p_T) \times 10^{-12} \left[mbc^3/ (GeV)^2\right].$$

These 3 formulas have been used for the whole energy range because no data exist for other energies.
Integrating the invariant cross-sections over the whole solid-angle we obtained the differential cross-sections for the production of $\overline{d}$, $^3\overline{He}$ and $^4\overline{He}$. Figure 1 shows the results for primary protons with an energy of 1000 GeV.
Using these differential cross-sections and an interstellar energy spectrum of protons given by Tan and Ng (1983) of the form:

$$j_p(T_p) = 2.0 \times 10^4 \, T_p^{-2.75} \, (m^{-2}sr^{-1}s^{-1} \, GeV^{-1}),$$

where T_p is the kinetic energy of the protons in GeV, the flux of antiparticles $\overline{d}$, $^3\overline{He}$ and $^4\overline{He}$ has been derived on the basis of the leaky box model with the mean escape length $\lambda = 5$ g cm^{-2} independent of energy (Gaisser and Levy, 1974) and under neglect of the inelastic interactions of the produced antiparticles.
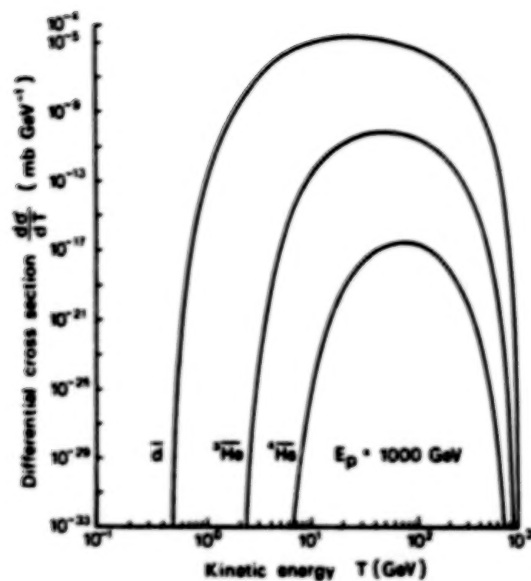
Fig. 1. The differential cross-section for the production of $\bar{d}$, $^3\overline{He}$ and $^4\overline{He}$ for a primary proton of 1000 GeV.

3. Results. Figure 2 shows the curves of the secondary fluxes in dependence from the kinetic energy of the produced antiparticles.
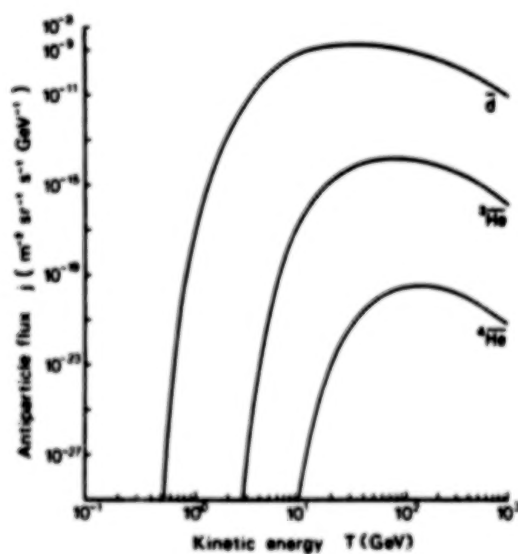
Fig. 2. The secondary flux of $\bar{d}$, $^3\overline{He}$ and $^4\overline{He}$ in dependence from their kinetic energy.

With these results the event rates for the secondary antiparticles could be calculated. Table I shows the values for the maximal flux using a geometry factor of $1 \text{ m}^2 \text{sr}$.

TABLE I

Event rates for the detection of secondary antiparticles for a geometry factor of $1 \text{ m}^2 \text{sr}$

Particle.	Event rate (yr^{-1})
$\bar{p}$ [a]	5.4×10^3
$\bar{d}$	4.7×10^{-2}
$^3\overline{\text{He}}$	4.4×10^{-7}
$^4\overline{\text{He}}$	9.4×10^{-13}

[a] The $\bar{p}$ event rate is calculated from the measured differential $\bar{p}$-flux of Buffington et al. (1981).

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ANALYSIS OF EXPERIMENTAL DATA ON INTERSTELLAR
ANTIPROTONS IN THE LIGHT OF MEASUREMENTS OF
HIGH-ENERGY ELECTRONS AND ^{3}He NUCLEI

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We have reexamined the interstellar antiproton
calculation in view of the recent progress in
measurements of interstellar electrons and ^{3}He
nuclei. It is found that the divergence between
our predicted antiproton flux and the existing
datum at very low energies is increased.

It appears that our proposed nonuniform galactic disk (NUGD) model
(1) can qualitatively explain the unexpectedly large flux of interstellar
antiprotons ($\bar{p}$'s). Nevertheless, it should be noted that some ambiguities
existed in the prototype of the model. For instance, it was unclear
what fraction of observed $\bar{p}$'s is of local origin. Moreover, previously
the value of cosmic-ray escape pathlength (λ_e) was suggested with quite
a large arbitrariness.

In order to improve the model itself we have compared the high-
energy electron spectrum predicted for it with measured data(2). This
comparison is significant in the estimation of astrophysical parameters
inherent in the model. Therefore, we find that in the observed proton
flux the fraction ϵ of the protons being of local origin is only 5 ± 1 %,
indicating that the dominant part of cosmic-ray protons is contained in
the distant component of cosmic-rays. Further, the deduced λ_e value in
the H_2 cloud region is about 3 times that suggested by the leaky box
model, which is consistent with our conclusion that the main part of
observed $\bar{p}$'s is produced in the H_2 cloud region(1).

Thus an improved calculation is performed to deduce the interstellar
$\bar{p}$ flux based on our newly obtained parameter values in the NUGD model.
In our calculation(see the model elements shown in Fig. 1 of OG 7.2-10)
the λ_e value in Box 1 or Box 2 is taken from the empirical relationship
given in Ref. (3) (hereafter we use the subscripts 1, 2, I and II to
express the quantities referred to Boxes 1, 2, I and II respectively),

$$\lambda_{e12}(R(GV/c)) = 35 \left(1 + \left(1.88 / R \right)^2 \right)^{-n/2} R^{-0.7} , \qquad (1)$$

where the HEAO 3 data(3) for both the B/C and N/O ratio prefer a value
of n=3, only the subiron to iron ratio requires a lesser value of n.
However, we note that the preliminary data on iron nuclei obtained by the
same group(4) also exhibit a flux increase with decreasing energy which
is faster than that predicted for the leaky box model. The reason for
it at present is unknown. Since one of the basic assumptions in our
NUGD model is that the 'leaky box' concept should be applicable to its
individual elements, for the time being the inconsistency shown above

makes it reasonable to neglect the data on iron-group of nuclei and keep n=3 in Eq. (1). Thus the deduced $j_{\bar{p}12}$ (i.e., the $\bar{p}$ flux predicted for the leaky box model) is shown in Fig. 1 as the curve OPLB, which is comparable with our previous prediction(the curve TLBF in Fig. 1).

In the deduction of the source term of $\bar{p}$'s in the H_2 cloud region the contribution of 'primary' $\bar{p}$'s, which originate from Box 2 and flow into Box II, should be taken into account (2). Thus the contributions coming from the 'primary' and the 'secondary' (i.e., locally produced) components of $\bar{p}$'s in $q_{\bar{p}II}$ are shown in Fig. 2 for the case of $\delta = 0.7$, where δ is the power index of the rigidity (R) dependence of λ_c. It appears that the dominant part of $\bar{p}$'s is indeed locally produced.
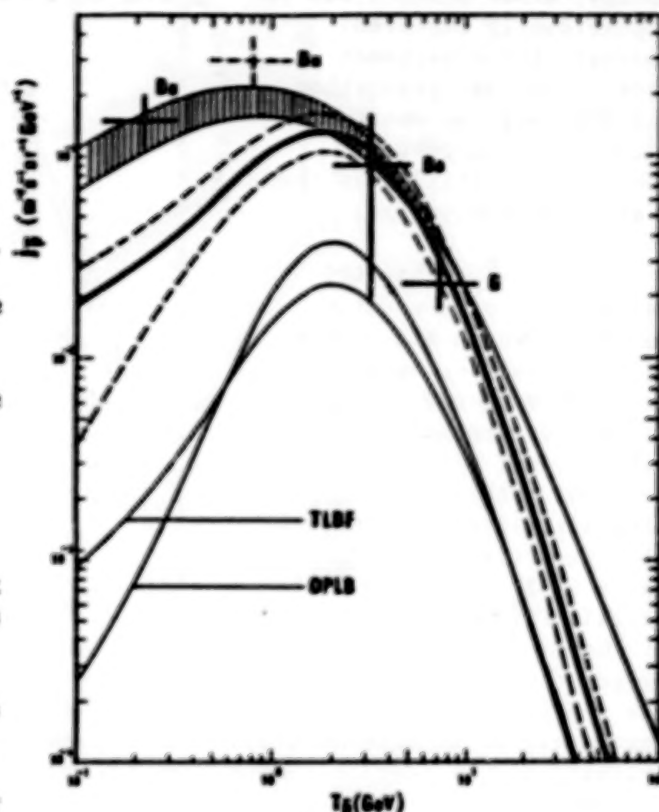
Fig. 1

Obviously, the estimation of the $\bar{p}$ flux in the dence H_2 cloud region, $j_{\bar{p}II}$, should be dependent upon the assumed value of cosmic-ray convection velocity, V. Nevertheless, the convection motion of cosmic rays should play a less serious role in view of the fact that 10 GeV cosmic rays have a diffusion coefficient of about 10^{30} cm^2/s (2). Therefore, the allowable range of the $\bar{p}$ flux may be estimated by assuming some extreme values of V. Here we will consider the cases of V = 0 (no convection motion) and V = 300 km/s (the estimated velocity of galactic wind for the normal galaxy(5)). Thus $j_{\bar{p}II}$ and the $\bar{p}$ flux after the adiabatic deceleration in the assumed boundary layer ($j_{\bar{p}de}$), and the $\bar{p}$ flux reaching the solar neighbourhood from Box II ($j_{\bar{p}de}$), are shown in Fig. 3 for the case of $\delta = 0.7$. Since the observed $\bar{p}$ flux in the solar neighbourhood should contain both the distant and the local components, so that we have

$$j_{\bar{p}NUGD} = (1 - \xi) j_{\bar{p}s} + \xi j_{\bar{p}12} . \qquad (2)$$

In Fig. 1 we compare our newly predicted $j_{\bar{p}}$ (the thick solid line) and its allowable range due to uncertainties of λ_{eOII} and δ (the region between both dashed lines) with our previous prediction (the shaded region) and the existing $\bar{p}$ data(6)-(8). It is found that the consistency of our new prediction with the measured data at $T_{\bar{p}}$, the $\bar{p}$ kinetic

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OBSERVED ANTIPROTONS AND ENERGY DEPENDENT CONFINEMENT
OF COSMIC RAYS: A CONFLICT?

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ABSTRACT

In the frame work of energy dependent confinement for cosmic
rays, the energy spectrum inside the source is flatter than
that observed. Antiproton ($\bar{p}$) observation suggests large
amount of matter is being traversed by cosmic rays in some
sources. As a result, secondary particles are produced in
abundance. We have calculated their spectra and it is shown
that the energy dependent confinement model is in conflict
with some observations.

1. Introduction. The observed secondary to primary nuclei in cosmic
rays decrease with energy suggesting that matter traversed by cosmic
rays depends upon energy. Therefore, it was postulated (Eg. Juliusson
et al. [1]) that the confinement of cosmic rays in the Galaxy is energy
dependent. Recent observations show that the behaviour of this depen-
dence is $\alpha R^{-\delta}$ above ~ 2 GV/c with δ = 0.6 to 0.7 [2,3]. This would
mean that the accelerated spectrum of cosmic rays has a spectral index
β = 2.15 to 2.05. $\bar{p}$ observations show that cosmic rays traverse a
large amount of matter inside some sources. Because of the flatness
of source spectrum, secondary particles are copiously produced [4], and
the effect of energy loss processes is less felt by the particles.
Recently, it is shown that supernova (SN) explosion in dense cloudlets
can explain $\bar{p}$ observations [5]. This work was based on the Nested
Leaky Box Model [6], in which cosmic ray source spectrum has β = 2.75.
In this paper, we calculate the secondary particle production in SN,
which explode in dense cloudlets, in the framework of energy dependent
confinement model. We then compare the spectra of γ-rays, electrons
and positrons with observation.

2. γ-ray Emission from Sources. We have established a set of coupled
differential equations to describe the propagation of protons, $\bar{p}$, $e^{\pm}$
inside SN envelope, by taking into account all energy loss processes
including adiabatic cooling during expansion [7]. The initially acce-
lerated spectra is obtained by normalizing the interstellar spectra at
2 GV/c and thus we obtained 1.65×10^4 $R^{-2.15}/(m^2.sr.s.GV/c)$ for nucleons
and 90 $R^{-2.15}/(m^2. sr. s. GV/c)$ for electrons. We consider that the
SN expansion continues in the cloudlet till about 50 $g.cm^{-2}$ matter is
being traversed by cosmic rays. Because of the flat spectrum of
nucleons, it is found that only 10% of the observed nucleons in cosmic
rays have to come from such sources in order to account for the observed
$\bar{p}$; the corresponding value for β =2.75 is 30% [8]. The effect of syn-
chrotron radiation on electron spectrum is also small and the spectrum
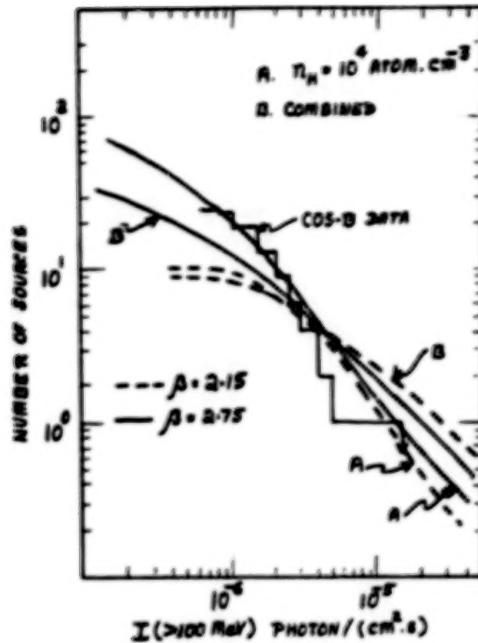
Fig.1 Integral distribution of γ-ray sources is shown as a function of intensity above 100 MeV. The dashed curves are for energy dependent model and the solid curves are for Nested Leaky Box model.

at high energies is not much depleted.

We have calculated the spectrum of γ-rays resulting from π^0 decay and bremsstrahlung processes. If 90% of the observed cosmic rays come from SN exploding in normal interstellar medium, the scaling required to estimate the total brightness of the source from the normalized interstellar spectrum is $\approx 10^{62}$. In order to calculate this number, we consider a galactic volume of R = 15 kpc and h = 0.5 kpc, in which cosmic rays are stored for 3×10^7 yrs. In this volume, the rate of SN explosion in interstellar medium is one in 30 yrs. We assume that acceleration is complete in ~200 yrs and the adiabatic cooling effective during the adiabatic phase. The number of SN required in cloudlets to account for the observed $\bar{p}$ is calculated and the relative number to that explode in interstellar space is found to be 0.129, 0.093, 0.075 and 0.061 for $n_H = 10^4$, 4×10^4, 10^5 and 2.5×10^5 atom.cm^{-3} respectively. Making use of these parameters, we have calculated the luminosity distribution of γ-ray sources in the Galaxy as described elsewhere [9].

We have shown in Fig. 1, the luminosity distribution of γ-ray sources for energies 100 MeV, assuming that the distribution of SN in the Galaxy is similar to the molecular hydrogen [10]. The dashed Curve A is calculated for $n_H = 10^4$ cm^{-3} and Curve B after folding in the observed density distribution of clouds [11]. These are compared with the Cos-B distribution [12], which is shown by the histogram. It is clear from this figure that there is no serious conflict with the data. For comparison, we have shown by solid curves the predictions with $\beta = 2.75$ [9]. We have also estimated the spectral hardness of γ-ray sources, which is defined as I (> 300 MeV)/ I(> 100 MeV). It is found that over the life of the SN, this varies only by small amount from
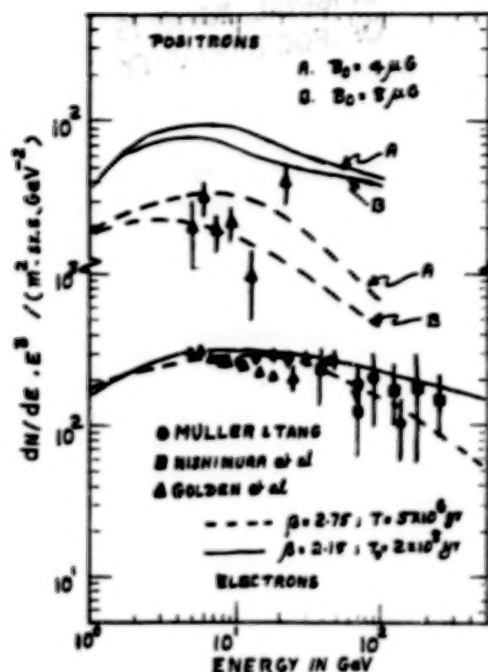
Fig. 2 *Electron spectrum is shown in the lower part and positron spectrum in the upper part. The solid curves are for energy dependent model and the dashed curves for Nested Leaky Box model.*

0.475 to 0.46, due to the flat input spectrum. This value is indeed in conflict with the observed values [12], most of which are much smaller.

3. Electron Spectrum. We have calculated the equilibrium spectrum of electrons and positrons in interstellar space by considering two kinds of source spectra $Q_{e\pm}$. One of them is from SN exploding in dense cloudlets, which contribute $\approx 10\%$ of the observed nucleons, and the other from SN explosion in normal interstellar medium. The equilibrium spectrum is obtained by solving the equation.

$$\frac{dJ_{e\pm}}{dt} = \frac{\partial}{\partial E} (J_{e\pm} \frac{dE_{e\pm}}{dt}) + Q_{e\pm} - J_{e\pm}/T(E) \qquad \ldots \qquad (1)$$

in which $T(E)$ is taken to be $T_0 E^{-\delta}$, and T_0 is varied to obtain a good fit to the data. We have plotted in the lower part of Fig. 2, the observed flux values from recent experiments [13-15]. The solid curve is the calculated spectrum using a value of $T_0 = 2 \times 10^8$ yrs. This value of T_0 is inconsistent with 1.4×10^7 yrs obtained from ^{10}Be data at low energies [16]. We have also shown the calculated equilibrium spectrum for $\beta = 2.75$ [17] with $T = 5 \times 10^6$ yrs, which is consistent with the observed value within errors.

Making use of the same value of T_0 obtained from the study of electrons, we have calculated the equilibrium spectrum of positrons. This spectrum is shown in the upper part of Fig. 2 by solid curves. The two curves A and B correspond to magnetic fields in the dense cloudlets assuming that the field strength scales as $(B_0 \sqrt{n_H})$ with $B_0 = 4$ and 8 µG respectively. It is clear that the observed spectrum [18] is not

in agreement with the calculations. If one reduces the value of B_0 or T_0, the deviation from the data would increase further. We have also shown the calculated positron spectrum for $\beta = 2.75$ [18] and one notices a good agreement with the observation.

4. Discussion. Many difficulties associated with the energy dependent confinement model have been pointed out earlier [19]. They include power requirement, streaming velocity at high energies and the smooth spectral shape extending to very high energies. We have shown here that, though the expected luminosity distribution of sources is not in conflict with the Cos-B data, the observed spectral hardening of γ-ray sources is not in agreement with the expectation. Secondly, the observed electron spectrum is clearly in conflict with the expectation [13]. Thirdly, the model predicts too large a flux of positrons. The above conclusions are further strengthened if the value of δ is indeed 0.7 [2].

The analysis made here is based on the hypothesis that antiprotons are produced in sources as secondary particles. However, if $\bar{p}$ comes from external galaxies [20], one may perhaps circumvent the present inconsistencies. However, it has been shown by Stephens [21] from a study of muon charge ratio at sea level that the extragalactic hypothesis and energy dependent confinement model cannot co-exist.

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ANTIPARTICLES IN THE EXTRAGALACTIC COSMIC RADIATION

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ABSTRACT

It may be possible to account for a previously puzzling feature - a "bump" in the energy range 10^{14}-10^{15} eV - of the cosmic ray spectrum by hypothesizing a primary extragalactic origin for the bulk of the observed cosmic ray antiprotons, although such an explanation is not unique. In this model, most of the cosmic rays above 10^{15} eV are extragalactic. We describe a method of testing this hypothesis experimentally.

1. Introduction. One of the most fundamental questions in cosmology is the question of the existence of antimatter in significant quantities in the universe. Does antimatter play an equal role with matter in the makeup of the galaxies? This question has now become a question of fundamental importance to physics as well. In the contemporary paradigm of grand unified gauge theories it is related to the question of the nature of CP violation at high energies (1,2). Recent theoretical work based on the concepts of grand unified theories has resulted in the development of a plausible baryon-antibaryon domain theory in which matter and antimatter are created in separate regions of survivable size to begin with (3-5). Various observational aspects of this theory have been previously discussed (6,7) and the subject of baryon symmetric cosmology has been recently reviewed elsewhere (8,9).

2. Primary Antimatter. The present status of cosmic ray antiproton measurements and the attempts to understand them have been recently reviewed (10) and an exegesis of the primary extragalactic origin hypothesis has also been recently given (11). We will discuss further implications of potential basic import to cosmic ray research here and we will also propose an experimental search program based on these considerations. We start with the hypothesis that the baryon symmetric domain cosmology leads to a flux of extragalactic cosmic rays consisting of roughly equal amounts of protons and antiprotons with the sources of these cosmic rays being primarily active galaxies (12) and with helium and antihelium nuclei being supressed by destruction processes in these sources (11). We assume that the galactic wind is too weak to keep out the extragalactic cosmic radiation. Observations favor the interpretation that the galactic wind is in reality a "breeze" (13).

The measured spectrum of cosmic radiation can be represented by a power

law in energy of the form $KE^{-\Gamma}$ with the spectral index $\Gamma = 2.75$ for several decades above the 10 GeV energy level. It appears likely that this radiation is produced primarily in galactic sources (14,15). Furthermore, the source spectrum of this radiation is expected to have a lower spectral index Γ_s than that observed at the earth which has been steepened by energy dependent propagation effects. A value for Γ_s of approximately 2.0 to 2.2 appears to be likely for two reasons. (A) Measurements of the ratio of secondary to primary nuclei in the cosmic radiation suggest that the mean lifetime in the Galaxy owing to trapping by the tangled galactic magnetic fields falls with energy as $E^{-\delta}$ where the most recently derived value (16) of $\delta = 0.7$. (B) The theoretical shock acceleration models for cosmic ray production currently favored (17) generally yield production spectra with Γ_s close to 2.
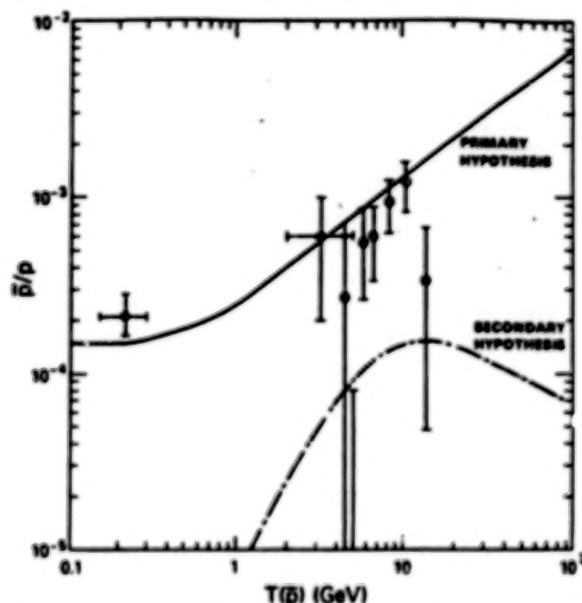
If we assume that there exists a general acceleration mechanism for generating cosmic rays which acts in both galactic and extra-galactic sources to give a universal source spectrum with $\Gamma_s = 2$, as is now thought to be the case with shock acceleration, then the extragalactic cosmic ray component should reflect this source spectrum. Thus, with the antiprotons assumed to be both primary and extragalactic and the bulk of the protons to be galactic, the expected ratio of antiprotons to protons should increase with energy as E^{δ}.

Figure 1. Observations and theoretical $\bar{p}/p$ ratios as a function of kinetic energy. The data points are from Refs.(18-20). The theoretical curves take account of solar modulation effects.

Taking $\delta = 0.7$, antiprotons could make up approximately one per cent of the cosmic ray flux at an energy of $= 500$ GeV and even ~ 50 per cent at higher energies. This has important observational implications (see section 3). The situation is indicated in Figure 1 which shows the present data on $\bar{p}/p$ ratios as a function of kinetic energy and the theoretical curve corresponding to a primary extragalactic antiproton flux. Solar modulation flattens the theoretical curve at low energies. Additional secondary production of antiprotons (as shown) is relatively unimportant. It can be seen that the theoretical curve for the extragalactic primary origin hypothesis provides an encouragingly good fit to the present $\bar{p}$ data. Thus, our hypothesis has possible observational support.

Figure 2 shows the effect of extrapolating the extragalactic intensity of both protons and antiprotons (this introduces a factor of two) with a spectral index of 2 to higher energies and superposing it on the galactic cosmic ray spectrum with index $\Gamma = 2.75$. Note that such an

extrapolation implies that the extragalactic and galactic cosmic ray fluxes become comparable at an energy of about 10^5 GeV and that extragalactic particles predominate above this energy. It is interesting that the resultant flattening in the spectrum occurs at this particular energy where there have been claims (22) of a flattening in the cosmic ray spectrum as inferred from measurements of extensive air showers. A steepening in the spectra of both the galactic and extragalactic components would be required by the observations for energies above 10^5 GeV.
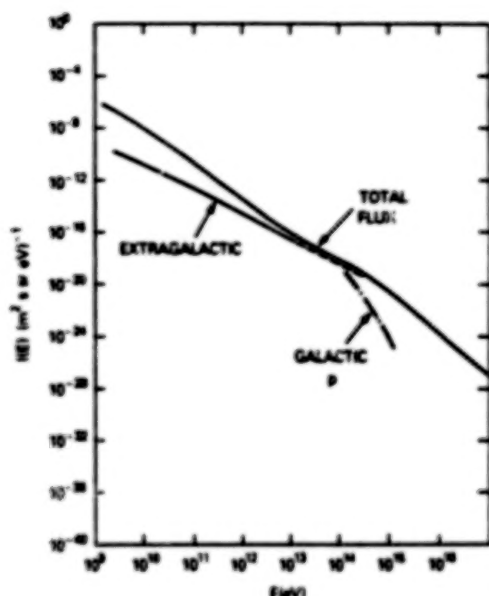
3. Experimental Tests. Since our model indicates that the antiproton-to-proton ratio which should increase with energy, measurements of the sign of the charges of cosmic rays at the highest practical energy and the determination of the spectra of the various charged components of the cosmic radiation up to that energy will provide a test of our hypothesis as well as the black hole hypothesis (21) and the photino hypothesis (Cf. Fig. 1 here with Fig. 2 of paper OG 6.1-9). Such a test requires the placement of the experiment above the atmosphere so that the incoming cosmic ray nuclei can be measured directly. Furthermore, the sign of their charges (and magnitude) may be measured by use of a superconducting magnet. A detector of

Figure 2. The effect of extragalactic primary protons and antiprotons on the total cosmic-ray spectrum according to the model discussed in the text. It can be seen that this model may account for the putative flattening in the observed cosmic ray spectrum near 10^{14} eV.

this type, with an attainable energy of about 500 to 1000 GeV, could be flown aboard a space shuttle (23,24). In addition, an emulsion stack experiment could be flown on a high altitude balloon or on the space shuttle to look for antihelium nuclei, even at the reduced level implied by our hypothesis. A polar orbit would be desirable to avoid the geomagnetic cutoff. In view of the almost impossible odds of creating a secondary ^{4}He antinucleus, the unambiguous detection of even one such particle would provide irrefutable evidence of primary cosmic ray antimatter. (The observed low-energy antiprotons in the cosmic radiation are also quite difficult to explain as secondaries from cosmic-ray interactions.)

If the $\bar{p}/p$ ratio is observed to continue to increase as $E^{0.7}$ or thereabouts at higher energies, then our hypothesis of extragalactic antiprotons from antimatter galaxies will have very strong support. This would rule out the photino and black hole hypotheses. The observation of antihelium nuclei would, as already mentioned, provide certainty. The extent to which non-observation of antihelium disproves our hypothesis is unclear, but if $\bar{\alpha}/\alpha \ll 10^{-5}$ (the value expected very

approximately on the basis of $\bar{a}$'s leaking from "normal" antimatter galaxies) then the difficulty would be severe.

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GALACTIC COSMIC RAY ANTIPROTONS AND SUPERSYMMETRY

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ABSTRACT

We consider the physics of the annihilation of photinos $(\tilde{\gamma})$ as a function of mass in detail, in order to obtain the energy spectra of the cosmic-ray $\bar{p}$'s produced under the assumption that $\tilde{\gamma}$'s make up the missing mass in the galactic halo. We then compare the modulated spectrum at 1 a.u. with the cosmic-ray $\bar{p}$ data. A very intriguing fit is obtained to all of the present $\bar{p}$ up to 13.4 GeV data for $m_{\tilde{\gamma}} \sim 15$ GeV. We predict a cutoff in the $\bar{p}$ spectrum at $E = m_{\tilde{\gamma}}$ above which only a small flux from secondary production should remain.

1. Introduction. It has recently been suggested (1) that annihilation from a dark matter halo made up of 3 GeV $\tilde{\gamma}$'s may account for the suprisingly large low-energy $\bar{p}$ flux reported in Ref. 2. Other interesting possibilities exist for producing such fluxes which are also of potential cosmological and astrophysical importance (e.g. Ref. 3 and OG 6.1-8). The photino hypothesis also affords a test for whether we live in a universe where supersymmetry (boson-fermion symmetry) is relevant. Indeed, measurements of cosmic-ray $\bar{p}$'s from $\tilde{\gamma}$ annihilation can enable the cosmic-ray physicist to determine the mass of the $\tilde{\gamma}$. This, however, requires a calculation of the energy spectrum of cosmic-ray $\bar{p}$'s produced in $\tilde{\gamma}$ annihilation and $\bar{p}$'s and modulation of this spectrum in order to directly compare with observed fluxes. We present here the results of such a calculation.

2. Photino (and Higgsino) Physics. Supersymmetry is a relatively new principle in particle physics which has been invoked to account for the "smallness" of the W-boson mass (compared with the grand unification scale) and possibly to incorporate gravity into a unified field theory. According to this principle, each ordinary boson and fermion has a supersymmetric partner and the lightest supersymmetric particle (LSP) should be stable. A prime candidate for the LSP is the $\tilde{\gamma}$ (or, more generally, a possible mass state admixture of the $\tilde{\gamma}$ (having gauge interactions) and neutral higgsino (having Yukawa interactions)). If such a stable particle is made in the early big-bang, it becomes a candidate for the dark matter in the universe (along with other possibilities such as massive neutrinos, axions, black holes, etc.). The mass density of such particles in the universe scales inversely with the annihilation cross section times velocity $\langle \sigma v \rangle$. A value near the critical density can be obtained by choosing a reasonable value for the prime unknown parameter involved in the calculation (4,5), viz., the mass of the scalar fermion which mediates the annihilation, $m_{\tilde{f}}$. For two particular values for the $\tilde{\gamma}$ mass, $m_{\tilde{\gamma}} = 3$ GeV, chosen in Ref. 1, and

$m_{\tilde{\gamma}}$ = 20 GeV, we obtain the following formulas for the mass density of photinos as a fraction of the closure density:

$$\Omega_{\tilde{\gamma}} = \binom{1.0}{0.4} \, h^{-2} (m_{\tilde{f}}/50 \text{ GeV})^4 \quad \begin{array}{l} , \, m_{\tilde{\gamma}} = 3 \text{ GeV} \\ \\ , \, m_{\tilde{\gamma}} = 20 \text{ GeV} \end{array} \tag{1}$$

where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. In both cases, the mass of the scalar fermion $\tilde{f}$ required to obtain $\Omega_{\tilde{\gamma}}$ = 1 is ~50 GeV, a value which may find some support in interpretations of the monojet events observed at the CERN p$\bar{p}$ collider (6). Photinos of mass much above 20 GeV will not give cosmologically significant mass densities.

The energy spectrum of the $\bar{p}$'s produced in $\tilde{\gamma}$ annihilations may be obtained from studies of quark-jet fragmentation in e$^+$e$^-$ collider experiments. In these experiments, the fractional energy distribution functions obtained for the various secondary particles produced are observed to scale with energy (7). We may write

$$\frac{1}{\sigma} \frac{d\sigma}{dx} = 2.89 \, \beta \, \left(\frac{s}{\beta} \frac{d\sigma}{dx} \right) \tag{2}$$

with the numerical factor in units of μb GeV^2. Here s is the square of the cms energy, β is the relative velocity and x is the energy of the $\bar{p}$ expressed as a fraction of the mass of the annihilating $\tilde{\gamma}$. From an analysis of the various experiments found in the literature, we find that the $\bar{p}$ distribution function can be represented as falling between upper and lower limits given by

$$\frac{s}{\beta} \left(\frac{d\sigma}{dx} \right) = \begin{cases} <8.5 \exp(-11x) + 0.25 \exp(-2x) \\ \\ >7.7 \exp(-14.5x) + 0.17 \exp(-2.5x) \end{cases} \tag{3}$$

The total annihilation cross section is given by (4)

$$\langle \sigma \beta \rangle = \frac{8\pi\alpha^2}{m_{\tilde{\gamma}}^4} \left[\sum_f q_f^2 \beta_f m_f^2 \right] \tag{4}$$

where the f's are the quarks and leptons (fermions) produced in the annihilation and $\beta_f = (1 - m_f^2/m_{\tilde{\gamma}}^2)^{1/2}$.

3. Fluxes from $\tilde{\gamma}$ Annihilation in the Galactic Halo. If we assume that the galactic halo mass is made up almost entirely of $\tilde{\gamma}$'s, from rotation curve determinations (see,e.g.(8)) we find that a uniform halo has a mass density on average of ~ 1 GeV/cm^3 within 10 kpc of the galactic center. A halo with an isothermal mass distribution would have a mean mass density at 10 kpc galactocentric distance of ~ 0.4 GeV/cm^3. Dividing by the photino mass $m_{\tilde{\gamma}}$ then gives the photino number density $n_{\tilde{\gamma}}$. The production rate of antiprotons produced by annihilation is

$$Q(E_{\bar{p}}) = n_{\tilde{\gamma}}^2 \sigma \beta \alpha_{\bar{p}} f(E_{\tilde{\gamma}}) \quad \text{cm}^{-3}\text{s}^{-1}\text{GeV}^{-1}, \tag{5}$$

where $\zeta_{\bar{p}}$ is the number of $\bar{p}$'s produced in the annihilation (determined by $m_{\tilde{\gamma}}$) and the spectral production function $f(E_{\bar{p}})$ is normalized so that its integral is unity. The diffusion coefficient for cosmic rays at 10 kpc (the solar galactocentric distance) in the energy range involved (rigidity P in GV) is (9)

$$D = 10^{26} \beta P^{0.7} cm^2 s^{-1} \tag{6}$$

which implies that the relevant antiprotons diffuse ~ 100-200 pc in the mean lifetime τ ~5 x 10^{14} s determined for the galactic disk in the solar neighborhood. The $\bar{p}$ flux in interstellar space is then

$$I_{\bar{p}} = Q_{\bar{p}}\beta c/4\pi = 1.2\times10^{24}Q \ cm^{-2}s^{-1}sr^{-1}GeV^{-1} \tag{7}$$

4. **Solar modulation.** The effect of solar modulation is most important in the low energy range of Ref.2. We have estimated the amount of proton modulation occurring during the relevant time period of the solar cycle, viz., June 1980, based on the Pioneer Helios-1 and ISEE-3 data (10). This yields expressions for the effective diffusion coefficient for modulation by the solar wind. The interstellar $\bar{p}$ spectrum may then be numerically modulated to compare with the observations (11).

Fig. 1 Unmodulated and modulated spectra for 3 GeV and 20 GeV photino annihilation compared with data and cosmic-ray secondary production spectra (CRS) and modulated CRS (MCRS).

5. **Results.** Fig. 1 shows the interstellar and modulated spectra obtained for 3 GeV and 20 GeV $\tilde{\gamma}$ masses, compared to the observations (2,12,13) and the standard secondary $\bar{p}$ calculations (14). The spectra are normalized to fall near the data points, however, such a fit is well within the uncertainty of the flux calculation. Both functions in eq. (3) yield similar results. Fig. 2 shows the $\bar{p}/p$ ratio as a function of energy for 3 GeV (A), 15 GeV (B) and 20 GeV (C) photino masses and the standard secondary production predictions (D). The data are from Refs. 2, 12, and 13.

There may be some evidence for a ~15 GeV photino mass cutoff in the highest data point. In any case, it is clear that (1) photino masses of

this order yield an annihilation spectrum with a shape and possible flux
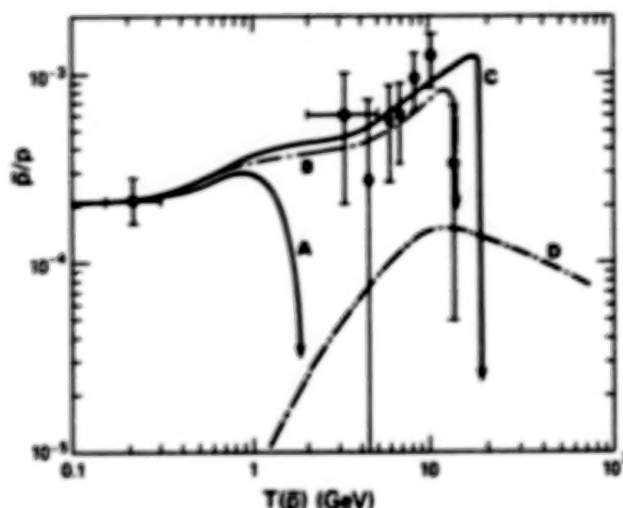
that fits all of the present data on cosmic-ray $\bar{p}$'s, and 2) owing to the kinematic cutoff in the annihilation spectrum, future high energy observations (15,16) to look for a cutoff in the $\bar{p}$ spectrum can, in principle, determine both the existence of a galactic photino halo and the mass of the photino itself.

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Fig. 2. $\bar{p}/p$ as a function of kinetic energy and data.

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detect stopping oxygen nuclei from 8 to 300 MeV/amu. For stopping iron, the energy range is 15 to 800 MeV/amu.

The exposure obtained, to date, on LDEF would make possible the detection of particle fluxes as low as 1.5×10^{-8} particles/meter sq.ster.sec. If the anomalous component ions are not fully ionized (Fisk et al., 1984), they should be found stopping in the HIIS detectors (O'Dell et al, 1977). Other sources of stopping heavy ions may be the inner radiation belt, or cosmic ray splash albedo. Chan and Price (1975) and Biswas et al. (1977) report observing stopping ions outside SKYLAB which were thought to be trapped radiation. The HIIS experiment has already accumulated more than 300 times the exposure of the SKYLAB experiment, so it may be possible to extend these earlier measurements. Humble et al. (1979) have considered the contribution from splash albedo and estimate that this effect is small, but Blanford et al. (1972) report detecting stopping heavy ions in balloon flights over Texas that they attribute to re-entrant splash albedo. This source may also contribute to the observed flux of stopping ions in the HIIS experiment.

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C-5

CHERENKOV - DE/DX - RANGE MEASUREMENTS ON
COSMIC RAY IRON GROUP NUCLEI

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KEYWORDS

ABSTRACT

We present a balloon experiment which combined a large area plastic
detector unit (4400 cm^2) with electronic dE/dx-C data.
The correlation of the electronic data with the range data of the
plastic detector stack was achieved by rotating plastic detector disks
which provided in this way the "passive" plastic detector with an in-
corporated time determination. The constant flux of cosmic ray particles
with charge Z greater than 2 was used to gauge the time resolving system
of the experiment.
Stopping cosmic ray iron group nuclei in the energy range 400 to 700
MeV/nuc have been identified using their electronic scintillator and
Cherenkov signals and their etch conelengths and range data. The precise
knowledge of the particle's trajectory proposes refined pathlength cor-
rections to th electronic data.
This three parameter analysis provides an absolute mass scale to check
whether the iron peak nuclei have the mass 56.

The Response of Ionization Chambers to Relativistic Heavy Nuclei

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ABSTRACT

As part of a recent calibration at the LBL Bevalac for the Heavy Nuclei Experiment on HEAO-3, we have compared the response of a set of laboratory ionization chambers to beams of $_{26}$Fe, $_{36}$Kr, $_{54}$Xe, $_{67}$Ho, and $_{79}$Au nuclei at maximum energies ranging from 1666 MeV/amu for Fe to 1049 MeV/amu for Au. The response of these chambers shows a significant deviation from the expected energy dependence, but only a slight deviation from Z^2 scaling.

1. Introduction

Gas filled ionization chambers were used on the Heavy Nuclei Experiment (HNE) on HEAO-3 (Binns et al., 1981). The response of such chambers is expected to be proportional to the energy deposited by the particle traversing them. At low energies this energy deposit is simply the ionization energy loss, while at high energies energetic knockon electrons are able to escape from the chamber, reducing the energy deposit.

To first order the ionization energy loss scales as the square of the particle charge Z, however at high Z this assumption breaks down. A more complete expression is given by Ahlen (1980, 1982), and predicts an energy loss rising slightly faster than Z^2. Such effects are important when identifying ultraheavy elements.

We have performed two calibrations of ion chambers at the LBL Bevalac using beams ranging from $_{25}$Mn to $_{79}$Au. The first, in 1982, was done with a prototype of the HNE ion chamber module which was essentially identical to that used in flight. Thus those data, reported in Garrard et al., 1983, are directly applicable to our flight experience at the energies calibrated. The second calibration, in 1984, used lab chambers which were made of thinner and more uniform materials, permitting better resolution and better knowledge of the beam energy in each ion chamber, at the cost of less direct relevance to the flight data. Figure 1 is a schematic drawing of the 1984 detector.

Particles entering the 1984 detector traversed ~0.1 g cm^{-2} of mylar in the upstream window, rather than the ~1 g cm^{-2} of aluminum honeycomb in the flight prototype; thus the energy loss in the window is much smaller and more uniform. Also, in the 1984 calibration the beam energy was measured with a magnetic spectrometer after being degraded to the calibration energy, rather than being calculated from an energy loss model.

The lab ion chambers had aluminized mylar electrodes (0.8 mg cm^{-2}) rather than aluminum screenwire (10 mil diameter, 62.5 mil spacing); thus the production and absorption of knockons is much more uniform. A Monte Carlo model of knockon

production correctly predicts the degradation in resolution caused by non-uniform production of knockons in the screen wire electrodes. This resolution degradation in the flight chambers tends to mask the relatively subtle deviations from Z^2 scaling.
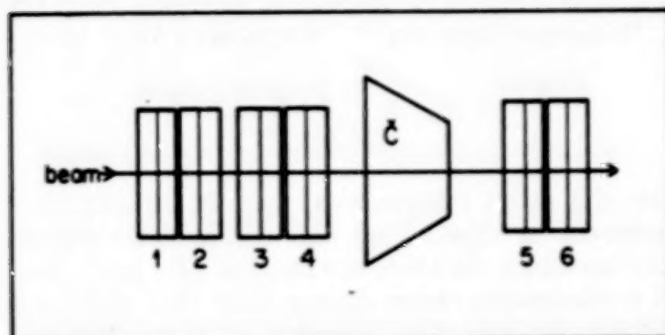
Figure 1. Schematic drawing of the 1984 detector, showing the six ion chambers.

In 1982 the ultraheavy capabilities of the Bevalac were new and we calibrated only on beams of ~1700 MeV/amu $_{25}$Mn and ~1000 MeV/amu $_{79}$Au. The 1984 calibration used beams of $_{26}$Fe, $_{36}$Kr, $_{54}$Xe, $_{67}$Ho, and $_{79}$Au at maximum energies ranging from 1666 MeV/amu for Fe to 1049 MeV/amu for Au.

2. Results of the 1984 Calibration

Figure 2 shows the response of chambers 1, 5, and 6 to $_{26}$Fe nuclei as a function of the energy at the midplane of the appropriate chamber, and compares their signals to the calculated dE/dx, arbitrarily normalized at 500 MeV/amu (requiring 27.9 eV per ion pair in the P-10 gas used (90% argon, 10% methane)). It is apparent that the signals fall below that predicted by dE/dx at energies above 700 MeV/amu. This loss of signal is somewhat surprising since at these energies we would expect knockons escaping from the exit window to be in equilibrium with those arriving from above, particularly for chambers 5 and 6 which have ~2 g cm^{-2} of upstream material. However, some of the decrease in observed signal may be due to knockons escaping from the sides of the chambers.

By interpolating to a particular energy we can construct a plot of signal versus Z at that energy. At low energies, the heaviest nuclei have an effective charge, $Z_{eff} = Z[1-\exp(-130\beta Z^{-2/3})]$, due to electron capture (Pierce and Blann, 1968). Figure 3 shows the pulse heights, scaled down by Z_{eff}^2, at four energies for Z = 26-79, using ion chambers 1, 5, and 6. The uranium data have not been included because the charge state in the magnetic spectrometer was uncertain for those beams whose energy had been degraded significantly. The straight lines represent a linear fit to the data, and it is apparent that there is a small negative non-Z^2 effect. The charge of an $_{82}$Pb nucleus would be underestimated by about 0.5 charge units at these energies, in contrast with the charge overestimate of +3 charge units observed in the calibration of the flight chambers.
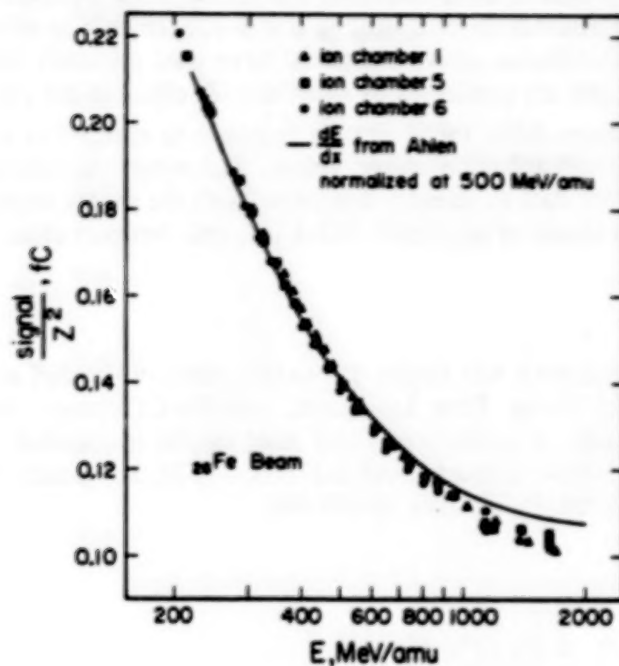
Figure 2. The response of chambers 1, 5, and 6 to $_{26}$Fe nuclei as a function of energy.
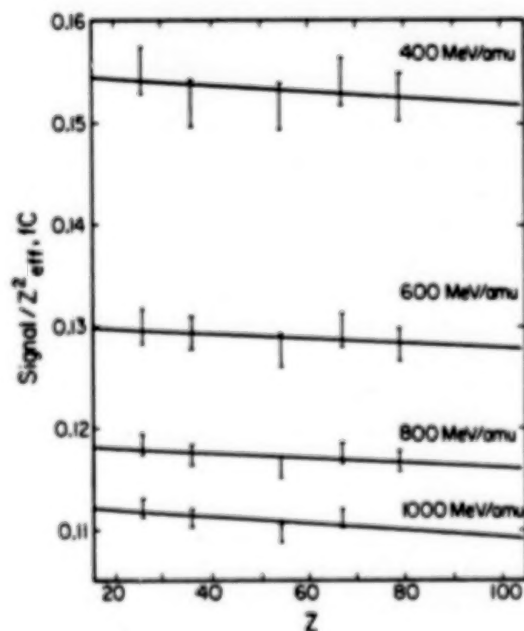
Figure 3. Response of chambers 1, 5, and 6 at four energies, scaled by Z^2_{eff}.

3. Conclusions

Although the non-Z^2 effects in these chambers differ from those observed in the prototype flight chambers, the assumption of Z^2 scaling is still not seriously in error. We also note that our published abundances above charge 50 have used primarily the Cerenkov detector to assign charges, and are unaffected by small non-Z^2 effects in the ion chambers.

Since the two calibrations differ, the ionization response to energy loss must be sensitive to details of the mass distribution above, below, and within the chambers. As a result we have used the flight data to directly determine both the energy dependence and effective non-Z^2 correction (Jones et al., (1985, OG 4.1-8) and Newport et al., (1985, OG 4.4-5)).

4. Acknowledgements

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MULTIPLE SCATTERING EFFECTS IN dE/dx-E INSTRUMENTS
FOR ISOTOPIC COMPOSITION STUDIES

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1. **Introduction**. The development of cosmic ray telescopes capable of
separating individual isotopes of heavy elements using the dE/dx-vs.-E
technique depended critically on the incorporation of precise trajectory
sensing elements into these systems. In typical implementations the
particle trajectory is derived from a set of position measurements made
prior to a particle's entering the first energy loss detector. The use
of the trajectory obtained in this way to correct energy loss signals for
the actual pathlengths through the detectors depends on the assumption
that the particle trajectory is a straight line. In order to resolve
iron isotopes the angle of incidence, θ, of the particle track (measured
from the normal to the detector surfaces) must be known rather
accurately.

When the angle of the cosmic ray's track through the ΔE detectors
must be known with this high precision, the effects of multiple Coulomb
scattering in the trajectory sensor, in the material between it and the
ΔE detector, and in the ΔE detector itself must be taken into account.
For example, when iron nuclei at 200 MeV/amu pass through a 1 g/cm^3 thick
layer of silicon, multiple scattering causes a distribution of the effec-
tive angles of the particle tracks through this layer. This
distribution, while centered on the angle at which the particles enter
the layer, has an rms spread of approximately 0.11°. For iron particles
traversing the layer at an angle of 30° this would lead to an uncertainty
in the calculated mass of slightly more than 0.1 amu. These effects
become increasingly more severe when one considers measurements of nuclei
of lower energy, or when absorbing materials of higher atomic number are
used.

In this paper we discuss an alternative approach to particle trajec-
tory determination which can provide a significant reduction in the
pathlength uncertainty in the energy loss detectors which is caused by
multiple scattering. This approach involves the measurement of the loca-
tions of the points at which the particle enters and exits the detector
and approximating the trajectory by a straight line between these two
points, rather than by a straight line through two points along the
particle's track before it entered the detector. In Section 2 the path-
length errors which result from these two approximations are compared.
In Section 3 one practical implementaton of the new approach is
described, and practical issues which limit its general applicability are
mentioned.

2. **Comparison of Pathlength Uncertainties**. Figure 1 schematically shows
the track of a heavy nucleus through a layer of material (such as a ΔE
detector), with the scattering greatly exaggerated. Also shown are the
approximations to this path which are obtained by using straight lines

through: a) points measured along the trajectory before entry into the detector, and b) the points at which the particle entered and exited the detector. Analyses by others [1] have shown that in case (a) the relative uncertainty in the pathlength through the detector is given by:

Figure 1.

$$\frac{\sigma_{\sec \theta}}{\sec \theta} = \frac{1}{\sqrt{6}} \cdot \tan \theta \cdot \sqrt{X} \; \sigma_\theta$$
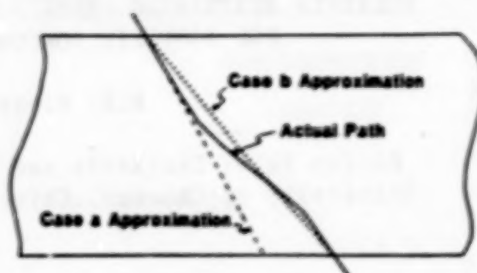
where θ is the nominal angle of the particle's track (measured from the detector normal), X is the detector thickness in g/cm^2, and σ_θ is the rms angle of deflection over a pathlength of $1 \; g/cm^2$. (Throughout this discussion we neglect the effects of particle slowing in the layer. Zumberge [2] has analyzed such effects, and the application of his approach to the cases considered here makes no qualitative changes in our results.)

For case (b) we have carried out a formal analysis in which the detector is subdivided into a large number of thin sublayers and the scatterings in each layer are treated as independent Gaussian random variables and their effects on the pathlength and on the point of exit from the detector are compounded. This analysis, carried out to first order in σ_θ, shows that the approximate trajectory (b) (see Fig. 1) agrees exactly with the true pathlength. The reason for this agreement is illustrated in Figure 2, in which we compare two paths - one involving a single scatter and the other a straight line agreeing with the first at its end points. The lenghts of the three segments shown are related by:

$$c = \sqrt{[a^2 + b^2 + 2ab \cdot \cos(\delta\theta)]}$$

which for small values of $\delta\theta$ reduces to:

$$c \simeq a + b - \frac{1}{2}\left(\frac{ab}{a+b}\right) \cdot (\delta\theta)^2$$

Figure 2.

That is, the difference in the two pathlengths is second order in $\delta\theta$. When more than one deflection of the particle's trajectory is considered, their combined effects also produce pathlength differences, but these all involve products of the individual scattering angles and therefore again only yield second order or higher effects.

In order to carry out a quantitative comparison between the pathlength errors in cases (a) and (b) we have chosen to perform Monte

Carlo calculations, rather than to extend our calculation for case (b) to second order. In addition, we have incorporated the effects of ionization energy loss in the Monte Carlo calculation, calculating the rms scattering angle in each sublayer using the actual value of the particle's velocity in that layer. In Figure 3 we compare our results for the two cases. Also shown, on the right hand abscissa, is a scale indicating the approximate contribution of these pathlength errors to the mass resolution for the measurement of iron isotopic composition. It can be seen that the determination of particle trajectories from the entry and exit points contributes negligibly to the mass resolution, while the use

Figure 3.

of a trajectory extrapolated from outside the detector leads to a mass error which, at large angles, could be the dominant source of mass uncertainty for measurements of iron isotopes.
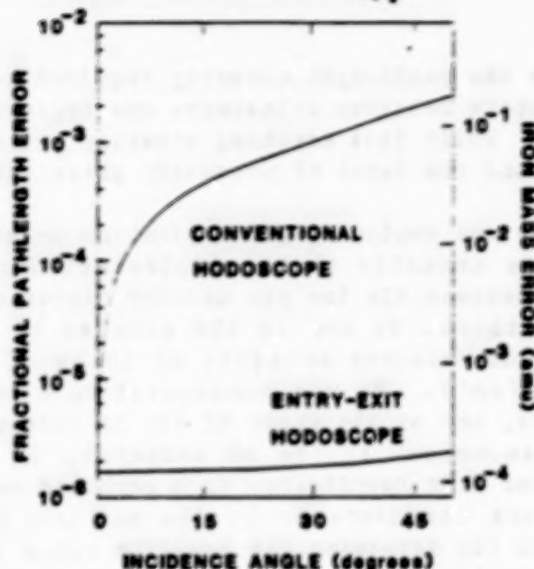
An additional source of pathlength uncertainty, which occurs when the trajectory is only measured before entry into the ΔE detector stack, results from scattering in any material (such as previous ΔE detectors) between the trajectory measurement and the measurement of ΔE which is being used for mass determination. For the same amount of material, these scatterings contribute a factor $\sqrt{3}$ more to the pathlength uncertainty than do scatterings in the ΔE detector itself [1]. Normally the best mass resolution is obtained from ΔE measurements made close to a particle's end-of-range, but multiple scattering effects may significantly degrade such measurements in systems where several other thick detectors must be penetrated subsequent to the trajectory measurement. These resolution-degrading effects should become noticeable for high-Z, high-angle events in the next generation of cosmic ray composition experiments utilizing silicon solid state detectors.

3. **Practical Applications.** The above considerations were based on the assumption that the locations of discrete points along a particle's track can be measured exactly. Under most practical conditions the errors made in measuring the locations of these points will dominate the multiple scattering error in case (b). If two orthogonal coordinates are each measured with an uncertainty σ_x at two faces of a detector of thickness Δz, the resulting uncertainty in the pathlength between these points is:

$$\frac{\sigma_{\sec\theta}}{\sec\theta} = \frac{1}{\sqrt{2}} \cdot \sin(2\theta) \cdot \frac{\sigma_x}{\Delta z}$$

The difficulty in implementing a practical entry-and-exit trajectory system stems mostly from the fact that the ratio $\sigma_x/\Delta z$ must be $\leq 10^{-3}$ to

achieve the pathlength accuracy required to resolve heavy isotopes. In solid state detector telescopes one typically has $\Delta z \leq 5$ mm, requiring $\sigma \leq 5$ µm. While this tracking accuracy is, in principle, achievable, it is far beyond the level of presently practical systems.

Systems employing gas ionization detectors for the ΔE measurement are more amenable to the implementation of an entry-exit trajectory system because the low gas density dictates that the detectors be relatively thick. We are in the process of constructing such a system in which a ΔE detector consists of 30 cm of gas at a pressure of 10 atm (~ 0.5 g/cm^3). We are incorporating a pair of single-wire proportional counters, one at the front of the ΔE detector and one at the back, in the same gas volume as the ΔE detector, to provide a determination of the entry and exit coordinates from combined measurements of drift time (to determine the distance of the particle track from the wire) and charge division (to determine the position along the wire). The large lever arm provided by the ΔE detector thickness (30 cm) makes it possible to derive a sufficiently accurate trajectory from position measurements made with a precision rather typical of gas-phase position sensitive detectors (~ 0.3 mm rms). While our present system uses P-10 gas (90% Ar, 10% CH$_4$) as the ionization medium, the entry-exit trajectory system should permit the use of heavier gases (such as Xe) to provide additional stopping power without introducing additional pathlength uncertainty. If a conventional trajectory system were used, the use of Xe instead of Ar would increase the multiple scattering induced pathlength uncertainty by a factor ~ 4, thereby severely restricting the solid angle over which satisfactory mass resolution could be attained (cf. Fig. 3).

4. **Conclusions.** Trajectory systems which provide the coordinates of a particle's track as it enters and exits each energy loss detector could, in principle, eliminate the contribution of multiple scattering to the mass error in dE/dx-E particle identifiers. The implementation of such systems appears most practical in systems using gaseous energy loss media. A detector system which can be used to experimentally test these results is now being developed.

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Hexagonal Uniformly Redundant Arrays for Coded-Aperture Imaging

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1. Introduction.

Uniformly redundant arrays are used in coded-aperture imaging, a technique for forming images without mirrors or lenses. This technique is especially important for the high energy x-ray and γ-ray region above 20 keV. In this technique, a mask consisting of opaque (closed) and transparent (open) areas is placed between the photon sources to be imaged and a position sensitive detector or a detector array. Each source casts a shadow pattern of the mask or aperture onto the detector. This shadow pattern may be viewed as an encoded signal for that source direction. If each possible source code is unique, the detected composite of overlapping shadow patterns may be decoded to produce an image of the source distribution.

Figure 1 shows a mask suitable for imaging. This mask consists of an array of open (white) and closed (gray) cells arranged in a periodic pattern. The unit pattern is outlined. The mask in figure 1 is a *uniformly redundant array*[1,2] (URA). URAs have an especially desirable property: the overlap between two source codes is independent of the source directions as long as the sources are sufficiently separated. Except for periodicity, this guarantees a unique decoding of the composite shadow pattern with a maximal immunity to statistical noise.

To date, most work on URAs has concentrated on those constructed on rectangular lattices. In this paper we focus on URAs constructed on hexagonal lattices, although many of the results are independent of the lattice type.

We will present complete details for the construction of a special class of URAs, the *skew-Hadamard URAs*, which have the following properties:

1) They are nearly half open and half closed.
2) They are antisymmetric (exchanging open and closed cells) upon rotation by 180° except for the central cell and its repetitions.

Figure 1. An HURA of order 79.

Some of the skew-Hadamard URAs constructed on a hexagonal lattice have additional symmetries. These special URAs that have a hexagonal unit pattern, and are antisymmetric upon rotation by 60°, we call *hexagonal uniformly redundant arrays* (HURAs). The mask in figure 1 is an HURA.

HURAs are particularly suited to our application, γ-ray imaging in high background situations. In a high background situation the best sensitivity is obtained with a half open and half closed mask. Furthermore, systematic variations of the detector background from position to position can be larger than the variations in detected flux due to sources. With a skew-Hadamard URA a simple rotation turns the mask into a near anti-mask, allowing exact position-by-position background subtraction. Also, the hexagonal symmetry of an HURA is more appropriate for a round position-sensitive detector or a close-packed array of detectors than a rectangular symmetry. This is especially true for shielded detector systems where compactness is at a premium.

2. Mathematical Structure of URAs

A URA is defined within a unit pattern which is repeated periodically. The number of cells in this unit pattern is the order v of the URA. Of these cells, k of them are closed and $v-k$ are open. The uniform redundancy property of URAs involves how frequently a given displacement between closed cells occurs. We will consider a cell within a repetition of the unit pattern as equivalent to the corresponding cell in the unit pattern, and will therefore define the difference between two cell centers as the vector displacement between them, folded back into the unit pattern. For a URA, all possible differences occur a uniform number λ times among the pairs of closed cell centers[2]. This property guarantees the uniform overlap of source codes discussed in the introduction[1,2].

The mathematical structure of a URA is that of an Abelian group difference set[3], which is specified by an Abelian (additive) group G of order v, and a set D of k elements of G with the property that any possible nonzero difference occurs exactly λ times between elements of D. For a URA the group G is the lattice translations modulo the periods of the mask pattern, and the set D contains those translations that take the central cell to a closed cell. The simplest examples of group difference sets are one-dimensional sets known as *cyclic difference sets* defined on the group of integers *mod v*. These play an important role in the construction of many URAs.

URAs in the class considered in this paper, the *skew-Hadamard URAs*, are nearly antisymmetric. That is, for any nonzero element in the group G, either it or its negative but not both, are contained in the difference set D[3]. These skew-Hadamard URAs are a subset of the *Hadamard URAs* which are nearly half open and half closed. Hadamard URAs are characterized by the parameters $v=4n-1$, $k=2n-1$, $\lambda=n-1$ for some integer n.

Johnsen[4] has proven two interesting facts about skew-Hadamard URAs :

1) All skew-Hadamard URAs have a *cyclic* group G, and therefore can be constructed from skew-Hadamard cyclic difference sets.
2) All skew-Hadamard cyclic difference sets are of prime order $v = 3$ *mod* 4 and can be generated from the quadratic residues *mod v* .

These facts allow us to present a construction for *all* antisymmetric or skew-Hadamard URAs.

3. Construction of Skew-Hadamard URAs from Quadratic Residues

We now present a simple procedure for generating any skew-Hadamard URA. An example constructed on a hexagonal lattice is shown in figure 2. The procedure consists of the following steps:

1) Choose the lattice on which the URA is to be constructed. The lattice is defined by picking two basis vectors $\bar{e}_0$ and $\bar{e}_1$. For our example we have chosen a hexagonal lattice, which has the basis vectors separated by 60°.

2) Choose as the order of the URA a prime of the form $v = 4n-1$. In our example $v = 23$.

3) Construct the order v skew-Hadamard cyclic difference set from the formula

$$D=\{1^2,2^2,...,(\frac{v-1}{2})^2\} \ mod \ v \qquad (1)$$

Figure 2. Construction of a skew-Hadamard URA of order 23.

4) Choose an integer r and label all the cells so that the cell centered at $i\bar{e}_0+j\bar{e}_1$ is labeled with

$$l = (i + rj) \ mod \ v \qquad (2)$$

and make all cells with labels in D closed. In our example $r=5$.

The heart of this procedure is the construction of the skew-Hadamard cyclic difference set in step 3. For a proof that this is a difference set see Baumert[3]. Step 4 transfers the difference set properties onto the lattice. This is done through the labeling, which transforms addition *mod v* to vector addition on the lattice modulo the resulting lattice periods.

The freedom available in this procedure rests in the choice of the lattice, the choice of the order *v*, and the choice of the multiplier *r*. The lattice type will determine what symmetries can occur. The possible orders form a rather dense set, the first few choices being $v=3,7,11,19,23,31,43,47,59,67,71,79$, and 83. The multiplier *r* determines the periods of the URA, and hence the shape of the unit pattern. Many of the *v* available choices result in URAs that are related by the symmetries of the lattice.

4. Hexagonal Uniformly Redundant Arrays

Of the large number of skew-Hadamard URAs, all of which can be constructed by the procedure in section 3, we wish to pick out those that have a hexagonal unit pattern when constructed on a hexagonal lattice. These we call *hexagonal uniformly redundant arrays* (HURAs)[5]. For an HURA each period when rotated by 60° is again a period. It can be shown from equation (2) that this is only possible if the multiplier *r* satisfies

$$r^2 = r-1 \mod v \tag{3}$$

This property has a simple geometric interpretation: a cell labeled *l* when rotated by 60° will have the label *rl mod v*. This feature, and the properties of quadratic residues modulo a prime, causes this restricted set of URAs to have a rotational antisymmetry upon rotation by 60° as well as 180°.

It can be shown that HURAs exist for order $v=3$ and any prime order of the form $12n+7$. If HURAs related by symmetry are considered equivalent, then for each of these orders there is a single HURA. The number of available HURAs is still large; figure 3 shows the number of HURAs with order *v* or less for *v* up to 10,000. In figures 4 through 8 we show examples of a few moderate order HURAs.
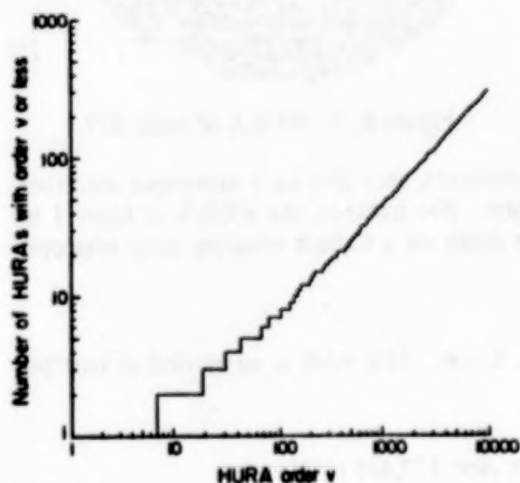
Figure 3. The number of HURAs with a given order or less.

Figure 4. An HURA of order 67.

OG 9.2-1
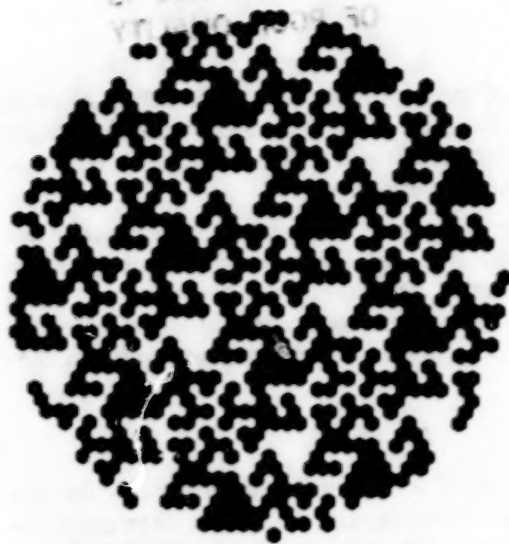
Figure 5. An HURA of order 139.
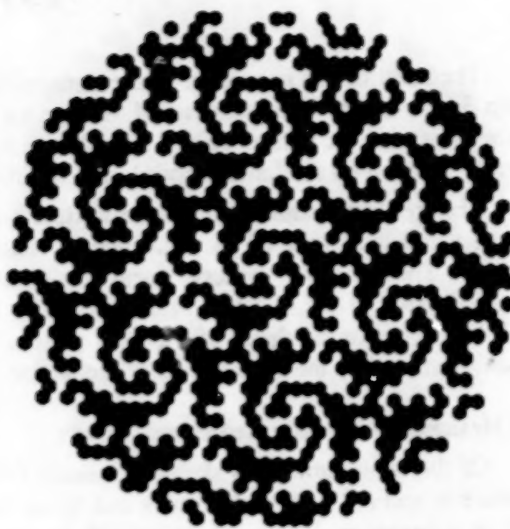
Figure 6. An HURA of order 151.
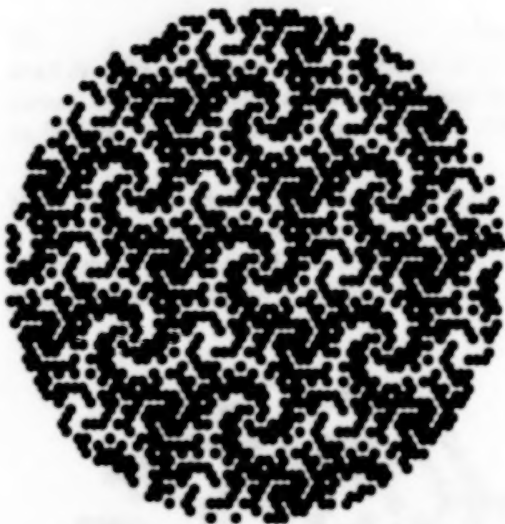
Figure 7. An HURA of order 331.
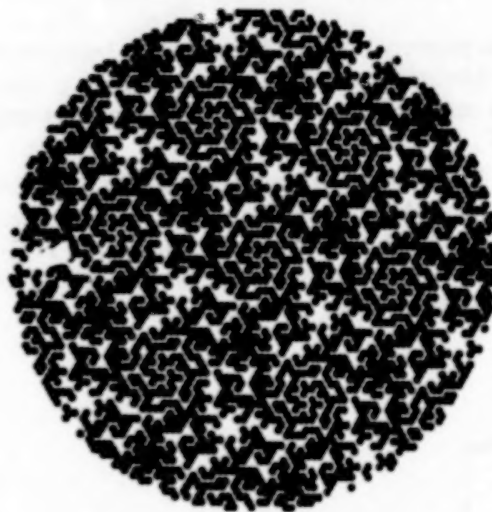
Figure 8. An HURA of order 619.

While HURAs are mathematically interesting constructs, they also have numerous attractive features for applications in astronomy instrumentation. For instance, the HURA of figure 1 is being implemented as a 115 kg lead coded-aperture mask on a Caltech imaging γ-ray telescope (see OG9.2-2).

5. Acknowledgments

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A Balloon-Borne Imaging Gamma-Ray Telescope

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1. Introduction. This paper describes a balloon-borne coded-aperture γ-ray telescope for galactic and extragalactic astronomy observations. The instrument, called GRIP (Gamma Ray Imaging Payload), is designed for measurements in the energy range from 30 keV to 5 MeV with an angular resolution of 0.6° over a 20° field of view. Distinguishing characteristics of the telescope are a rotating hexagonal coded-aperture mask and a thick NaI scintillation camera. Rotating hexagonal coded-apertures and the development of thick scintillation cameras are discussed in *Cook et al.* [1984 and 1985, referred to as Papers I and II respectively].

2. Instrument Description. The basic elements of GRIP are shown in Figure 1. The telescope consists of a shielded detector system separated by 2.5 m from a lead coded-aperture mask. The primary detector is a position-sensitive scintillator which records the characteristic spatial pattern of photons cast by a γ-ray source through the mask.

The mask is made of lead hexagons 2 cm thick and 2.5 cm across (flat-to-flat), supported by an Al honeycomb sandwich which is transparent at γ-ray energies. The aperture contains 2000

Figure 1.
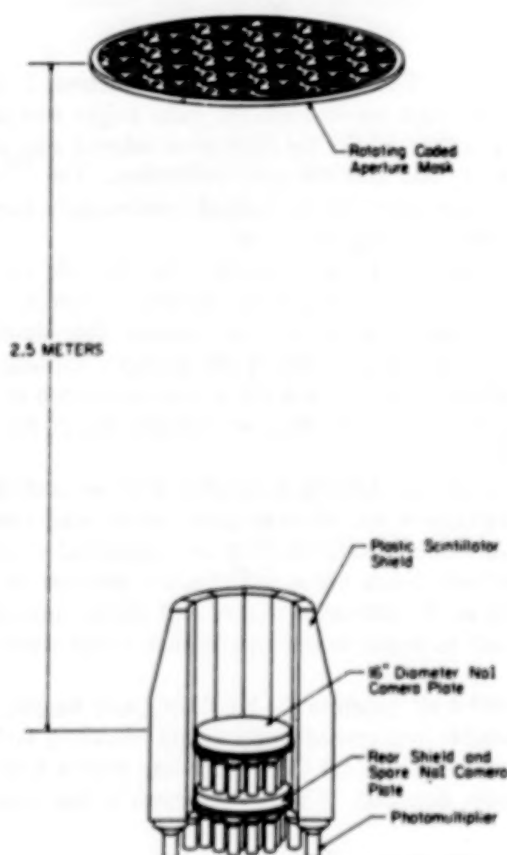
Table I: GRIP Balloon Telescope

Primary Detector	41 cm x 5 cm NaI Anger Camera
	Position Resolution: <5 mm rms
	(0.1-5 MeV)
Shield	Back Plate: 5 cm NaI
	Side: 16cm plastic scintillator
Mask	Hexagonal URA: 2000 cells (2.5 cm)
	Rotation Rate: 1 rpm
	Spacing: 2.5 m from NaI detector
	Size: 1.2 m diameter x 2 cm (Pb)
Energy Range	0.03 - 5 MeV
Energy Resolution	8.3 keV FWHM @ 50 keV
	70 keV FWHM @ 1 MeV
Imaging	Resolution: 0.6°
	(1070 pixels in 20° FOV)
	Angular Localization: 3 arc min
	(10σ source)

OG 9.2-2

hexagonal cells of which half are open and half contain a lead hexagon. The cell pattern (see Figure 2) forms a hexagonal uniformly redundant array (HURA) that is optimal for coded-aperture imaging. HURA's are discussed in more detail in Paper I and in paper OG 9.2-1 in these proceedings.

Continuous mask rotation imposes an additional level of coding on the γ-ray signal. Due to the antisymmetry of the coded-aperture pattern under 60 degree rotation (open and closed cells interchange for all but the central cell) the γ-ray signal at each position on the detector is time-modulated with a 50% duty cycle. This feature allows a complete background subtraction to be performed for each detector position once every 20 seconds assuming a 1 rpm rotation rate. In addition, the continuous rotation permits extension of the field of view to 20 degrees, greatly increasing the number of pixels imaged [Paper I].

The primary detector is a NaI(Tl) camera plate 41 cm in diameter and 5 cm

Figure 2.
GRIP coded-aperture mask pattern.

thick manufactured by the Harshaw Chemical Co. The NaI is viewed by nineteen 3 inch Hamamatsu R1307 photomultiplier tubes (PMT's) which are individually pulse height analyzed. The PMT gains are calibrated continuously using pulsed LED's for short term relative gain calibration and an [241]Am tagged γ-ray source for long term absolute gain calibration. The [241]Am source is situated 1m above the coded-aperture mask and can be imaged continuously during flight, allowing a thorough checkout of the mask-detector imaging system.

Background suppression is provided by an anti-coincidence shield. On the side are 12 plastic scintillator modules which form a cylinder ~16cm thick. Each module is viewed by a single 5 inch Hamamatsu R1416 PMT. The lower shield section is a NaI camera plate identical to the primary sensor. Further background suppression is provided by the primary scintillation camera itself. The PMT pulse heights contain information on the depth of the interaction in the crystal. Thus the lower half of the detector can be used as an effective "integral shield" for the reduction of background at low energies [Paper II].

The telescope is mounted on an elevation pointing platform suspended from an azimuthal torquing system. Azimuthal stabilization and orientation are achieved using active magnetometer feedback to the azimuthal torque motor. Elevation orientation is under command control. Two Schonstedt MND-5C-25 magnetometers provide 2-axis aspect information accurate to 1.5 arc minutes. This aspect information is recorded in the telemetry stream and allows correction of the event positions for pointing inaccuracies such as displacement and rotation of the telescope field of view.

For the initial flight of GRIP, we will record all nineteen 12 bit PMT pulse heights for each event. Event rates of up to 5×10^3/s are possible and consequently a data recording system with a 1 Mbit/s data rate is required. We have developed a 1.4 Mb/s recording system with 25 Gbyte capacity using commercial VCR's and audio digitizers. This development is described in paper OG 9.3-11 in these proceedings.

The characteristics of the instrument are summarized in Table I.

3. Instrument Performance.

Position and Energy Resolution: The GRIP scintillation camera has been designed to have ~1cm FWHM or better position resolution over an energy range from 100 keV to 5 MeV. Figures 3a

and 3b show histograms of γ-ray event positions computed by a maximum likelihood method for beams of photons of 122 keV (^{57}Co) and 662 keV (^{137}Cs) incident on the center of the detector [Paper II]. At the lower photon energy, the 10.5mm FWHM of the distribution is dominated by photon statistics. At the higher photon energy, both Compton scattering and photon statistics contribute to the 7.0mm width of the distribution. The effect of Compton scattering is most noticeable in the extended non-Gaussian tails of the distribution.

Although the standard deviation of the distribution of computed event positions increases with energy, the FWHM of the distribution continues to narrow due to an increase in the yield of optical photons per γ-ray event [Paper II]. As a consequence, the point-source angular resolution of the GRIP telescope improves with energy. The primary effect of Compton scattering is a reduction in sensitivity due to a removal of events from the core to the tail of the position distribution.

The energy resolution of the GRIP scintillation camera is comparable to that of single PMT NaI detectors. We have measured a resolution of 7% FWHM at 662 keV.

Imaging: Figures 4a and 4b are laboratory images of 122 keV and 662 keV γ-ray sources taken with the fully configured GRIP telescope. The sources were suspended 10m from the coded-aperture mask and the imaging algorithms were adjusted to account for the finite distance to the source. The images demonstrate the ability of the telescope to locate and resolve point sources at γ-ray energies.
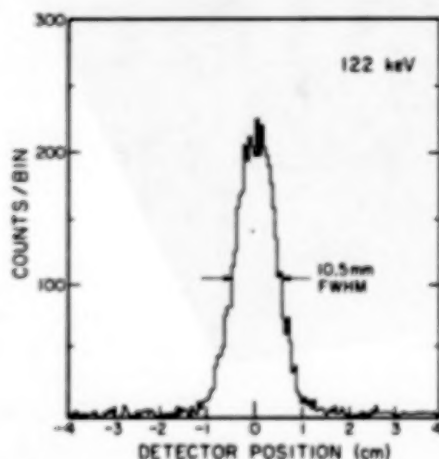
Figure 3a. Histogram of computed event positions showing position resolution at 122 keV.
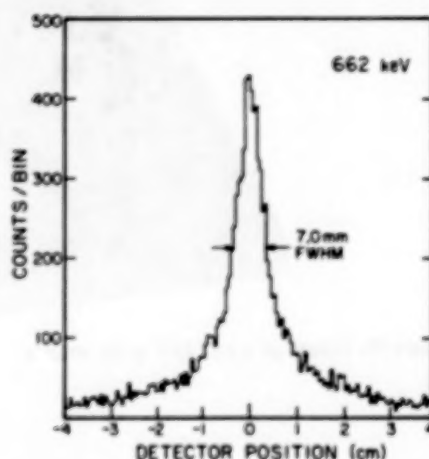
Figure 3b. Histogram showing position resolution at 662 keV.

Effective Area and Sensitivity: The geometrical imaging area of the GRIP scintillation camera is approximately 615cm^2. This area is determined by the maximum radius (~14 cm) for which good position resolution can be maintained. Additional factors determining the imaging effective area are the point-spread position determination function shown in Figure 3, the full energy detection efficiency, and the mask contrast [Paper I]. Figure 5 shows a plot of imaging effective area versus energy for the GRIP telescope.

The instrument sensitivity depends on the observed background which depends on such factors as flight location, zenith pointing angle, shielding, and instrument mass. We estimate our sensitivity to be approximately 1×10^{-5} ph/cm^2 s kev at 100 keV and 1×10^{-6} ph/cm^2 s kev at 1 MeV for a 3σ 8 hour observation from equatorial latitudes.

4. Flight Plans. The GRIP telescope is scheduled for an initial flight from Palestine, Texas in Fall 1985. Observing targets include the Cygnus region, NGC4151, and the Crab region. Future flights are anticipated from both the northern and southern hemispheres.
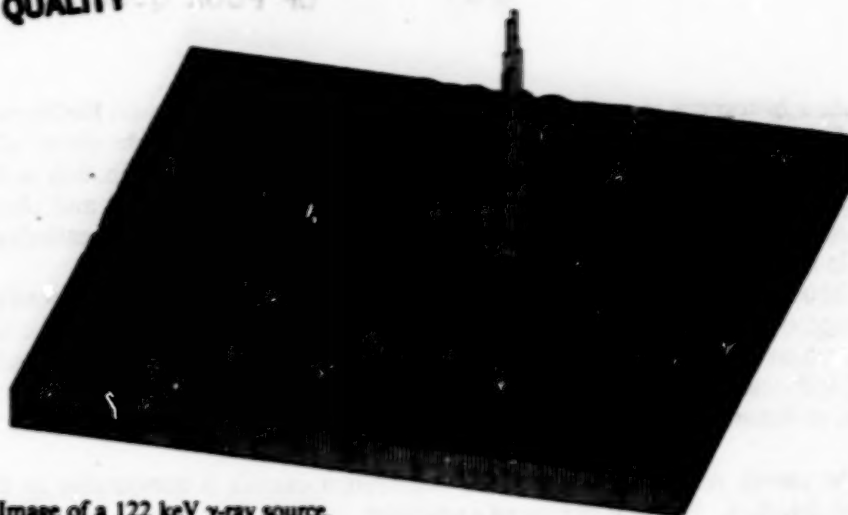
Figure 4a. Image of a 122 keV γ-ray source.

Figure 4b. Image of a 662 keV γ-ray source.

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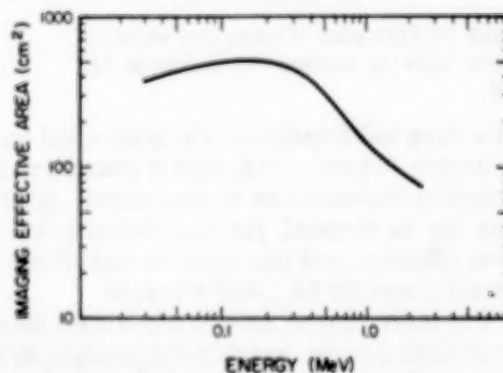
Figure 5. Effective area of the GRIP tele-
scope taking into account position resolu-
tion, full-energy detection efficiency, and
mask contrast.

A CODED APERTURE IMAGING SYSTEM
OPTIMIZED FOR HARD X-RAY AND GAMMA RAY ASTRONOMY

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ABSTRACT

A coded aperture imaging system has been designed for the Gamma-Ray Imaging Spectrometer (GRIS). The system is optimized for imaging 511-keV positron-annihilation photons. For a galactic center 511-keV source strength of 10^{-3} $cm^{-2}s^{-1}$, the source location accuracy is expected to be ±0.2°.

1. **Introduction** Current gamma-ray spectrometers observing in the 70 keV to 10 MeV nuclear-line energy range have poor source localization capabilities. They typically have broad fields of view (~ 10° FWHM) and no imaging systems. Recent discoveries of a number of gamma-ray sources with lines in their spectra (1,2,3) have increased interest in building spectrometers capable of mapping the source regions. An example is the positron annihilation line at 511 keV from the direction of the galactic center, whose location is known only to within ±4° (4). This large error circles several galactic-center X-ray sources in addition to the compact radio source Sgr A near the dynamic center of the galaxy. Localizing the line emission is currently one of the major goals in gamma-ray line astronomy.

The most promising technique for mapping in this energy range is coded aperture imaging using Uniformly Redundant Arrays (URAs). The basic idea is to place an array of blocking elments in the instrument aperture whose pattern is chosen such that the shadows cast on the detectors by sources at different locations in the field of view (FOV) give linearly independent sets of detector signals (5). The signals measured during an observation can then be uniquely deconvolved to give maps of the sky. Several papers have been written (6-10) discussing the application of coded aperture imaging to low-energy gamma-ray astronomy.

We are currently building a balloon-borne spectrometer to be flown in fall 1986 called the Gamma-Ray Imaging Spectrometer (GRIS) that will have a URA imaging system. In this paper we describe the imaging system and present the results of laboratory and computer simulations of its performance. A general description of the GRIS instrument is given in a companion paper (11).

2. **Description of the Imaging System** The Ge detectors in the GRIS instrument are located in every other cell of a 7.5 cm lattice as shown in Figure 1. The mask is a URA with a 3x5 element unit cell. It is located 1.5 m above the detectors and is arranged on a 7.5 cm grid. The

opaque elements are individual NaI blocks 6.8 cm square by 7.6 cm thick, each viewed by its own photomultiplier tube. Calculations and simulations we performed during the instrument design phase showed that it was essential for the mask to be active in order to achieve low levels for the instrumental line background at 511 keV and the continuum background over the entire spectrum.
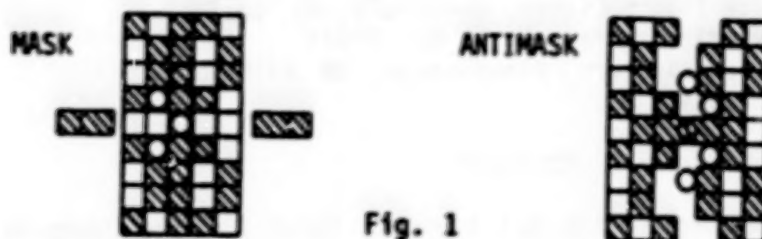
MASK   ANTIMASK

Fig. 1

Another feature of the GRIS imaging system that is essential for high-background observations is the ability to alternate between mask and antimask (see, e.g., ref. 7). The antimask is the complement of the mask, having opaque elements where the mask is open and vice versa. The incident gamma-ray flux is therefore square-wave modulated by the alternation, which is the optimum modulation for background subtraction. Normally mask-antimask systems have a separate structure for both the mask and antimask, each of which move in and out of the field of view. By a novel technique that reduces instrument weight and size, the GRIS mask is itself converted into its own antimask as illustrated in Figure 1. The mask divides into halves while two independent elements rotate into the center.

Both the mask and antimask also move as units left and right one cell so that a detector is located under each of the 15 elements in the mask unit cell at least once. In this way the 7-detector GRIS array is made to act like a 15-detector array in terms of its imaging capability. To produce a map, the mask system moves through 6 positions (3 mask, 3 antimask).

The maps produced by the imaging system have 15 sky bins arranged in a 3x5 matrix. The bins are each 3° square as determined by the mask cell size and the detector-mask separation. The region mapped is therefore 9°x15°. As will be shown below, this bin size and mapping region are a good match for the hard X-ray source distribution in the galactic center direction.

3. Imaging Sensitivity and Resolution   There is a decrease in sensitivity that all imaging systems suffer compared with non-imaging wide FOV systems which occurs when a source is not in the center of a sky bin. This is due to the fact that the source signal in the detectors is not fully modulated. The effect can be as large as a factor of 2.2 in sensitivity if the source is at the corner of four bins. To reduce this variation in sensitivity across the map and also increase the number of effective pixels in the final map, we will use an offset pointing technique. The basic idea is that the pointing direction of the instrument is changed between imaging cycles so that a given source appears at

different locations in the different sky maps. By changing the pointing 1° at a time in a 3x3 grid, the 3° sky bins are divided into 1° pixels. The final map then has an approximately uniform sensitivity that turns out for a single point source to be ~1.4 times poorer than a wide FOV instrument. The 3° bin size combined with the finite detector size gives the imaging system a point-spread function FWHM of ~4°.

The localization accuracy of the centroid of a point source image depends on the source strength and the number of sources in the field, but is in general much better than the 4° beam width. For the GRIS mask and detector arrangement operated in the offset pointing mode, the accuracy to which the position of a point source of strength S (photons $cm^{-2}s^{-1}$) can be determined is given by

$$\text{source location accuracy } (1\sigma) = 1.4 \ \theta \frac{\sigma_S}{S} \qquad (1)$$

where θ is the bin size of the mask (3°), and σ_s is the uncertainty in the flux measurement that would occur for a wide FOV observation. For a galactic center 511-keV line flux of 10^{-3} ph $cm^{-2}s^{-1}$ observed by GRIS for 8 hours at 3.5 g cm^{-2} atmosphere depth from Alice Springs, Australia, the value of σ_s/S is better than 1/20. Hence, GRIS will be able to localize the source position to within ±0.2°, which will be more than an order of magnitude improvement over the present best position (4).

4. Laboratory Tests and Computer Simulations A special laboratory test setup of the GRIS imaging system was assembled using NaI detectors in place of the Ge array and Fe and Al mask elements in place of the NaI elements. The detector and mask geometries were similar to those of GRIS except that the laboratory detector-mask separation was 45 cm instead of 1.5 m. This gives 9° sky bins, and was done to reduce the effects of the nonparallel gamma-ray beam produced by the radioactive source used in the laboratory. An ^{241}Am source was located 10 m from the detectors on a large, precise x-y positioning system. Figure 2 shows a map generated in the laboratory of a single on-axis source. The 9 offset pointing maps were combined into a final map with 3° pixel size (three times GRIS). The laboratory data were taken with very high statistical significance (~.1%) and then noise was added to the detector signals by computer. The noise level was chosen such that each unblocked detector signal was a 1.7σ measurement. This corresponds to a measurement of total significance $\sigma_s/S = 0.06$ in Equation (1).

To better understand the mapping capabilities of the GRIS imaging system, a computer simulation of the galactic center was performed. The computer simulation assumed a full 8-hour observation with GRIS of the 20-80 keV X-ray range from Alice Springs. Included in the galactic center direction were the 3 strongest sources (GX1+4, GCX-1, and GX5-1), with intensities assumed to be those measured by HEAO A4. In order to make the simulation as realistic as possible the data were "taken" using offset pointing, rotation of the image in the FOV, different length mask-antimask intervals during transit, and the expected instrumental background (12). Figure 3 shows the results, with the three sources clearly resolved.
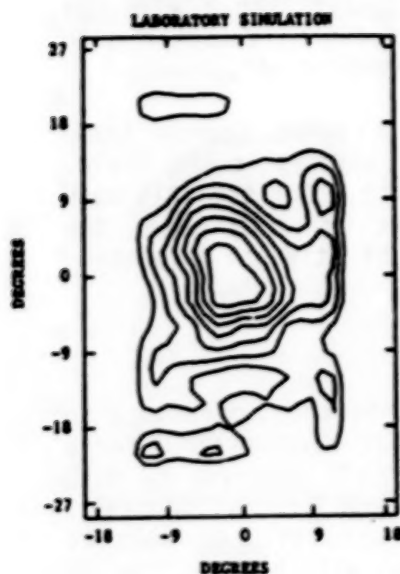
Fig. 2
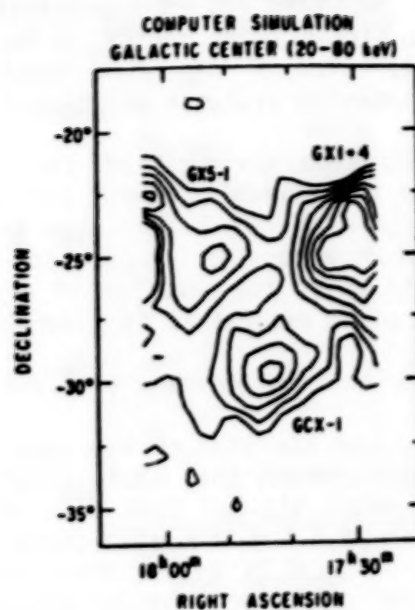
Fig. 3

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THE GAMMA-RAY IMAGING SPECTROMETER (GRIS):
A NEW BALLOON-BORNE EXPERIMENT FOR GAMMA-RAY LINE ASTRONOMY

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1. INTRODUCTION High resolution gamma-ray spectroscopy is a relatively new field that holds great promise for further understanding of high energy astrophysical processes. Preliminary results such as the annihilation radiation from the galactic center (Leventhal et al. 1978; Riegler et al. 1981), the ^{26}Al line from the galactic plane (Mahoney et al. 1984) and cyclotron lines from neutron stars (see e.g. Trumper et al. 1978) may well be just the initial discoveries of a rich and as yet undeveloped field. When the high resolution gamma-ray spectrometer (GRSE) was removed from the GRO payload NASA decided to initiate a balloon program to permit continued development and improvement of instrumentation in this field, as well as continued scientific observations. The Gamma-Ray Imaging Spectrometer (GRIS) is one of the experiments selected as part of this program. The instrument contains a number of new and innovative features that are expected to produce a significant improvement in source location accuracy and sensitivity over previous balloon and satellite experiments.

2. EXPERIMENT DESCRIPTION The basic instrument consists of an array of seven coaxial n-type germanium detectors surrounded by a thick active NaI shield/collimator. Located above this assembly is an active NaI coded-aperture mask for imaging and precise source location. The instrument performance is summarized in Table 1, and the central (pointed) section shown in Figure 1. The seven germanium detectors are each enclosed in individual cryostats. This design (rather than a single large multi-detector cryostat) was chosen for two principal reasons: 1) minimization of internally produced background (to be discussed in more detail later) and 2) ease of replacement of individual detectors, as well as upgrades and modifications.

A new concept has been introduced in the design of the germanium detectors wherein the cathode (outer surface layer) is divided into segments. The active germanium volume is therefore effectively divided into a stack of pancake-shaped detectors each ~1 cm thick. This takes advantage of the fact that over most of the relevant energy range the majority of photons undergo more than one interaction before they deposit all of their energy in the germanium crystal. Furthermore, the great majority of the background events over this same energy range are single point interactions. The resultant background suppression and improvement in sensitivity will be discussed later in more quantitative terms.

TABLE 1.

SUMMARY OF EXPERIMENT CHARACTERISTICS

Energy Range	0.02 to 10 MeV
Detector Size	6.5 cm dia. x 6.5 cm length nominal (Up to 7.5 cm detectors can be accomodated if available.)
Total Detector Area	232 cm^2 (309 cm^2 for 7.5 cm detectors)
3 Sigma Narrow Line Sensitivity	4.6×10^{-5} cm^{-2}-sec^{-1} at 60 keV 1.4×10^{-4} cm^{-2}-sec^{-1} at 511 keV 4.8×10^{-5} cm^{-2}-sec^{-1} at 2 MeV
Fields-of-view	20° FWHM coarse 3° x 3° FWHM fine 9° x 15° imaging
Imaging Pt. Spread Function (FWHM)	4°
Source Location Accuracy	$\pm$ 0.2° for f = 10^{-3} cm^2-sec^{-1} at 511 keV
Pointing Accuracy and Stability	$\pm$ 0.1°
Experiment Power	233 W
Experiment Weight	1500 kg
Telemetry Rate	56 K bits/sec
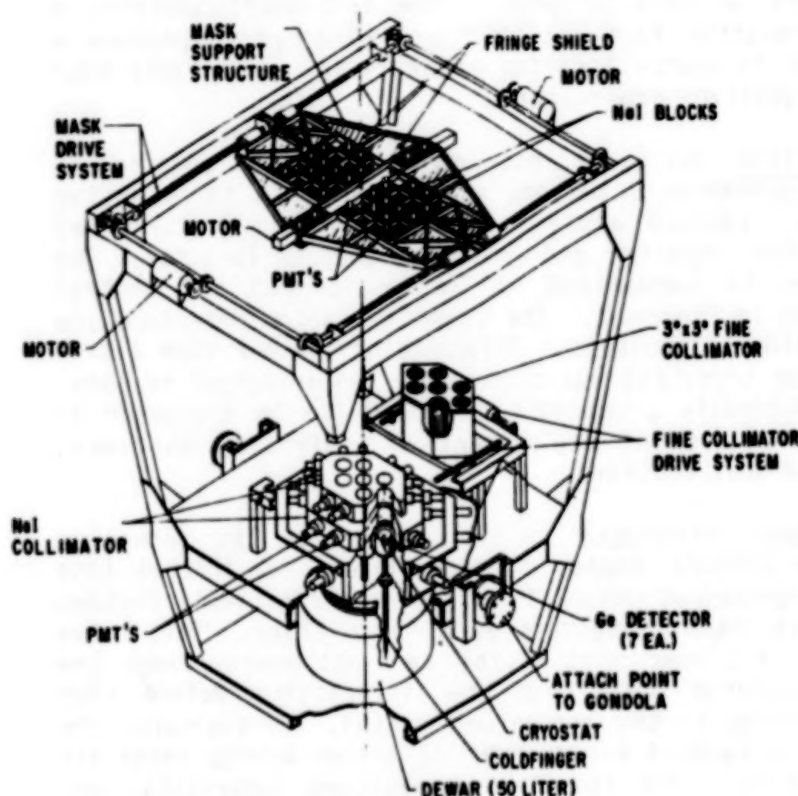
Fig. 1. GRIS pointed section.

The germanium detector array is cooled conventionally by a LN$_2$ dewar located beneath the detectors. NaI polyscin was chosen for the shield because of a) its relatively low cost, b) its high light output which allows a low threshold to be set and c) its fast response time which results in a lower overall shield dead time.

An active, uniformly-redundant mask system is used to generate sky maps

Fig. 1. GRIS pointed section.

over a 9^0x15^0 field-of view. A detailed descripion if the GRIS imaging system is presented elsewhere in these proceedings (Gehrels et al. 1985). The mask is constructed from blocks of NaI scintillator since a passive mask would result in an unacceptably high 511-keV background. We have chosen a mask/antimask configuration for this experiment since it provides a direct unambiguous determination of the instrument background. We have discovered a unique method whereby the mask can be converted into its own antimask by a simple motion of components. This reduces the total amount of scintillators required by approximately a factor of two. The system is designed such that the mask can be completely removed from the 20^0 FOV defined by the NaI collimator. In this configuration the instrument will operate in the usual on-source/off-source mode. This mode will be used in observations where the ultimate instrument sensitivity is required as well as for observing the diffuse galactic plane emission.

A passive fine collimator has been included for observing single isolated hard X-ray sources. Its primary purpose is to reduce the diffuse x-ray contribution to the overall background. It can be moved in and out of the field-of-view during the flight to allow maximum flexibility of the observing program. When it is in place the mask is moved out of the FOV.

A conventional azimuth-over-elevation pointing system with a momentum wheel for azimuth control will be used. Coarse pointing control will use the earth's magnetic field as a reference. A CID camera will be used to image star fields and the sun to obtain an independent and more accurate measure of the absolute pointing direction. The system is expected to have an overall accuracy and stability of ~ ± 0.1^0.

3. INSTRUMENT BACKGROUND AND SENSITIVITY Extensive modelling of the GRIS instrumental background has been performed (Gehrels 1985). The primary sources of this background are:

Continuum

1) Diffuse X-ray and atmospheric background photons entering through the experiment aperture.
2) Elastic collisions of secondary neutrons with Ge nuclei.
3) Beta-decay from cosmic-ray induced radioactivity in the Ge detectors.
4) Leakage of high energy atmospheric background photons through the shield.

Lines

1) De-excitation of nuclei in the Ge detectors that have been excited by primary cosmic rays and secondary neutrons.
2) Beta$^+$-decay of excited nuclei in the passive material surrounding the Ge detectors.
3) Pair-production due to high-energy atmospheric background photons interacting in the passive material surrounding the Ge detectors.

The effect of atmospheric gamma rays has been modelled using a Monte

Carlo program. A complete analysis of the effect of all possible cosmic-ray interactions has been carried out. This has involved examining ~ 2000 different interaction channels. These calculations have led to a number of key results that have had a profound effect on the design of the GRIS experiment. These are summarized as follows:

1) Nearly all of the important beta-decays go into the ground state. This means that there is no accompanying gamma-ray and that the energy deposition in the Ge is localized. Rejection of single-point interactions will therefore produce a significant supression of the continuum background.

2) Passive material inside the shield and in the FOV is a significant contributor to the background. This has led to the choice of an active mask and to a minimal-mass cryostat design.

3) The shield thickness and threshold are critical. This has lead to the choice of NaI for the shield.
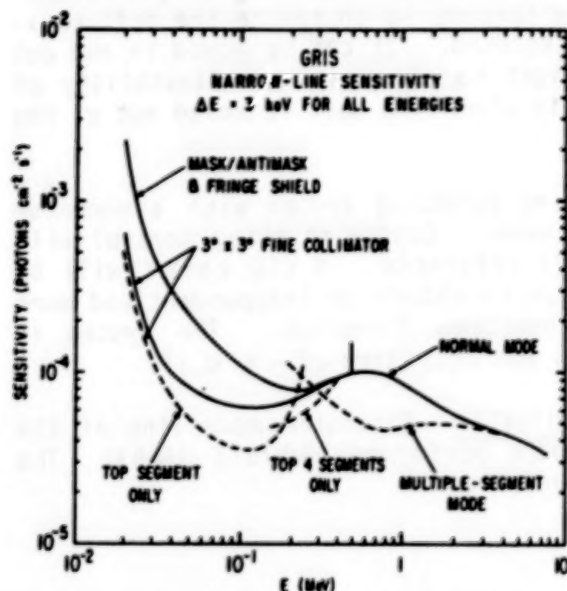
The results of these calculations have been compared with previous balloon results and found to be in excellent agreement. The resultant sensitivities are plotted in Fig 2. and represent typically a factor of ~5 improvement over the best previous balloon and satellite measurements.

Fig. 2. GRIS narrow line sensitivity. Cases for different segment requirements are shown.

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MODELING A HIGH ENERGY GAMMA-RAY TELESCOPE

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1. Introduction. We have developed a Monte Carlo program to simulate a high energy gamma-ray telescope using a coded aperture mask (CAMTRAC). The ultimate purpose of the calculation will be to determine the optimum design parameters for such an instrument. The model can also used to ascertain under what conditions CAMTRAC performance is superior to that of conventional telescopes which employ electron-positron pair direction as the sole means of determining gamma ray direction.

2. Procedure. The CAMTRAC telescope is assumed to consist of a coded aperture mask below which is located a position sensitive gamma-ray detector. It is assumed that an energy measurement is made for each converted photon. The model telescope is characterized by the following parameters:

   an energy dependent gamma-ray conversion efficiency,

   an energy dependent point spread function (PSF) for the determination of the gamma-ray direction from the pair direction,

   an energy dependent PSF for the measurement of the gamma-ray conversion point in the detector plane,

   a mask pattern, cell size and distance of the mask from the detector plane,

   an energy dependent transmission for the opaque cells in the mask,

   a resolution function for the energy measurement made on individual converted photons.

The source of photons is characterized by:

the integrated number of photons incident on the detector
from a point source,

the integrated number of photons per unit solid angle
incident on the detector from a uniform background,

an energy spectrum for both point source and background
photons which varies as E^{-2}.

A computational run consists of generating a set of data and then
analyzing it to determine whether or not a point source is apparent in
the data set and, if so, to determine its position. The analysis method
used is an adaptation of the maximum likelihood method used by
A.M.T. Pollock, et al.(1) to search for extragalactic point sources in
the COS-B data. In our application of this method, the likelihood
function,

$$W(\underline{r},X) = \sum_i \ln[S(\underline{r} - \underline{R}_i;E_i)T(E_i)X + (1-X)/\Omega]$$

is formed for each of several hundred points in a selected region of the
sky about seven degrees in diameter. The summation is made over all
events in the data set. $\underline{r}$ is the angular position of the point on the
celestial sphere where the function is being evaluated, $\underline{R}_i$ is the point
on the sphere to which the gamma ray pair direction is pointing for event
i, E_i is the measured energy of the photon, and $S(\underline{r}-\underline{R}_i;E_i)$ is the
normalized angular PSF. $T(E_i)$ is the mask transmission if the event in
question lies in the shadow of an opaque portion of the mask for a photon
coming from position $\underline{r}$ in the sky, otherwise it is 1. X is the fraction
of the set of events in the data that originate from a point source as
opposed to background. Ω is the solid angle subtended by that portion of
the sky from which the data set is drawn. The argument of the logarithm
in the summation is the probability of observing the event i if there is
a point source at position $\underline{r}$, from which a fraction X of the events
originate. At each point, $\underline{r}$, the maximum in $W(\underline{r},X)$ is determined in the
range $0 < x < 1$. The difference between this maximum and $W(\underline{r},0)$,
called λ in reference 1, is the quantity whose maximum is sought in the
region of the sky searched. The position of this maximum could be
considered to be the point that has a maximum probability of containing a
source.

To compare the CAMTRAC system to a conventional telescope, the same
calculation can be performed without a mask. In this case, the procedure
used for calculating the point source position is exactly the same as
that used for the CAMTRAC case except that the factor $T(E_i)$ is replaced
by 1 in the expression for $W(\underline{r},X)$. The CAMTRAC telescope will detect
fewer photons for a given incident flux because of absorption by the
mask. In addition, the decoding process implicit in any algorithm that
searches for the mask shadow in the distribution of conversion points
introduces noise in the likelihood function, $W(\underline{r},X)$. This noise is worse
when the number of point source photons is small.

2. Results. The table below shows the source location accuracy, expressed as r.m.s. error in source location, for two different levels of background and four point source intensities. The intensities are expressed as the total number of photons incident on the telescope above 10 MeV. As can be seen, the CAMTRAC detector has a source location accuracy superior to the conventional telescope by a factor of three in those cases where the point source intensity is most intense. The maximum point source intensity given in the table corresponds to a source of approximately the intensity of the Crab exposed to a detector one square meter in area for four hours. The greater of the two background levels corresponds approximately to the background that one would experience from the diffuse galactic radiation in the anti-center region under the same conditions of exposure. The statistical error in the computed values shown in the table is 15 to 25%.

R.M.S. SOURCE LOCATION ACCURACY, MINUTES OF ARC

	CAMTRAC		CONVENTIONAL	
Background (ph/sr) =	1.2×10^5	0.6×10^5	1.2×10^5	0.6×10^5
Source (ph)				
5000	1.4	1.7	4.3	5.2
2500	5.6	4.4	7.0	8.9
1250	32.6	48.0	19.2	14.8
625	85.0	90.8	64.9	63.1

4. Conclusions. A simple model is used in this simulation and the variables of the CAMTRAC system have not been optimized. However, the results show that the coded aperture mask system holds the promise of greatly improving the accuracy of locating point sources of gamma rays. In addition, it can be expected to improve the resolution of structure in extended sources of gamma rays.

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SECONDARY GAMMA-RAY PRODUCTION IN A CODED APERTURE MASK.

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1. Introduction. The application of the coded aperture mask to high energy γ-ray astronomy will provide the capability of locating a cosmic γ-ray point source with a precision of a few arc-minutes above 20 MeV (1). Recent tests using a mask in conjunction with drift chamber detectors have shown that the expected point spread function is achieved over an acceptance cone of 25° (2). A telescope employing this technique differs from a conventional telescope only in that the presence of the mask modifies the radiation field in the vicinity of the detection plane. In addition to reducing the primary photon flux incident on the detector by absorption in the mask elements, the mask will also be a secondary radiator of γ-rays. In this paper we consider the various background components in a CAMTRAC (Coded Aperture Mask Track Chamber) telescope and compare Monte-Carlo calculations with recent measurements obtained using a prototype instrument in a tagged photon beam line. This instrument is described elsewhere in this conference (3).

2. Secondary Background Production in a Mask. There are several mechanisms by which photons may be generated in a mask. Charged particles may generate γ-rays via bremsstralung, π^0-production or spallation in the mask material. By using veto counters, in front of and behind the mask, it is estimated that the contribution due to these components will be $< 10^{-5}$ γ's per incident particle, and therefore they can be neglected. Neutron interactions in the mask may produce secondary γ's through neutron capture or inelastic scattering. Butler et al. (4) have shown that this component is negligible, being $< 10^{-6}$ γ's per incident neutron for photon energies above 10 MeV. Gamma-rays incident on a mask may Compton scatter, or produce pairs within the mask material, that generate secondary photons by bremsstralung of the first generation electron(s), or (if an electromagnetic cascade is induced) by the secondary electrons. This component is potentially the most troublesome since in some of these

interactions none of the electrons will reach the veto counters.

3. Monte-Carlo Calculations. Monte-Carlo calculations have been carried out using the EGS electron-photon transport code of Ford and Nelson (5). Mono-energetic photons were allowed to fall normally on lead slabs of various thicknesses and the secondary photon and electron energy and radial distributions recorded. These distributions were found to agree, within statistical uncertainty, with those derived using the calculations of Messel and Crawford (6) and the experimental data of Darriulat et al. (7) In Fig. 1 we consider the various components that emerged from a 2.73 RL tungsten slab as a function of incident photon energy. A secondary photon threshold of 12.5 MeV was assumed in the calculations, this

value being representative of the lower limit of our telescope. The various contributions arise as follows; F_1 is the transmitted component (i.e. $F_1 = e^{-\mu(E)t}$ where $\mu(E)$ is the linear attenuation co-efficient of the mask material and t is the mask thickness), F_2 is the fraction of incident photons that generated secondary γ-rays, F_3 is the fraction of incident photons in which secondary γ-rays were also accompanied by an electron with a kinetic energy > 1 MeV, and F_4 is the fraction of incident photons

Fig. 1 The fraction of the various classes of events emitted from a 2.73 RL tungsten slab as a function of incident photon energy. Refer to the text for the definition of the symbols used.

that produced secondary γ-rays and no electron ▶ 1 MeV that left the slab. Therefore $F_2 = F_3 + F_4$. A scintillation counter placed immediately behind the slab will veto component F_3, and thus F_4 represents the intrinsic secondary background due to the mask. The energy spectrum of the unvetoed secondary component, integrated over 2π steradians, was found to be well represented by the empirical function;

$$dN(E,\bar{E}) = 3.79 \times 10^{-2} E^{0.96} \bar{E}^{-a} \exp(-1.054 \times 10^{-2}E) \qquad (1)$$
$$\times \exp(-47.17 \bar{E} E^{-1.55}) d\bar{E} \quad \gamma's \,/\, \text{incident photon MeV}$$

$$\text{where } a = \begin{cases} 0.843 + 3.6 \times 10^{-3} E - 6.3 \times 10^{-6} E^2, & 20 \leq E \leq 400 \text{ MeV} \\ 1.29, & E > 400 \text{ MeV} \end{cases}$$

and E and $\overline{E}$ are the incident and secondary γ-ray energies respectively. By comparison with Monte-Carlo data it is estimated that the average error in $dN(E,\overline{E})$, determined by Eq. 1, is < 10% over the incident energy range 20 to 600 MeV and secondary energies $1 < \overline{E} < E$.

In Fig. 2 we consider the case for a spectrum varying as E^{-2} normally incident on a mask consisting of equal open and opaque elements. The various components are shown separately integrated over 2π steradians. The band in the Fig. encompasses single and multiple secondary photon emission. For any detection system placed immediately behind the mask the true detector background would lie within these bounds. It can be seen from Fig. 2 that the unvetoed secondary component constitutes < 5% of the incident γ-rays. Further, since this component drops more rapidly than the incident flux ($\sim E^{-3}$ as opposed to E^{-2}) it can be neglected for energies > 200 MeV. It should be noted that for a practical telescope with a mask

Fig. 2 The various contributions to a detector counting rate for an E^{-2} spectrum normally incident on a tungsten mask of thickness 2.73 R.L.

and a detection area of 1 m^2, separated by 1 m, the measured unvetoed background will be approximately a factor of 1.2 lower than that shown at energies < 20 MeV due to the angular distribution of the secondary γ-rays. The median of this distribution ranges from about 15° to 3° for secondary energies 10 MeV to 200 MeV. Since this is much greater than the angular size of the unit mask cell at the detection plane, the secondary γ-rays will not reproduce the mask pattern, and will therefore constitute an almost uniform background level.

4. Experimental. It can be seen from Fig. 1 that the most efficient production of unvetoed secondary photons occurs for incident γ-ray energies of $\sim$100 MeV. For this reason secondary γ-ray spectra have been measured at a range of incident photon energies ranging from 23 to 400 MeV using a CAMTRAC telescope at the tagged photon facility at CEN Saclay,

France. Here we report preliminary results for normally incident
γ-rays of energies 27, 48, 90 and 108 MeV. The mask used during these
runs was a 2.73 RL tungsten checkerboard of unit cell size 6.3 mm. A
counter in front of the mask vetoed charged particle induced events,
while a counter behind the mask tagged those events in which a secondary
γ-ray was also accompanied by a charged particle that did not trigger the
detector anti-coincidence. A calorimeter located behind the track cham-

ber measured the photon energy with
a typical energy resolution of 57%
FWHM at 100 MeV. Fig. 3 shows the
total secondary spectra measured
at various incident energies. These
were determined by comparing runs
with and without the mask in place.
For comparison the results of
Monte-Carlo calculations are also
shown from which it can be seen
there is reasonable agreement. Also
shown in Fig. 3 is the spectrum of
events for which a charged particle
(> 1 MeV) was also detected in the
counter behind the mask, from which
we conclude that the unvetoed
secondary component produced in the
mask comprises at worst $\sim 10^{-3}$ γ's per incident photon per MeV.
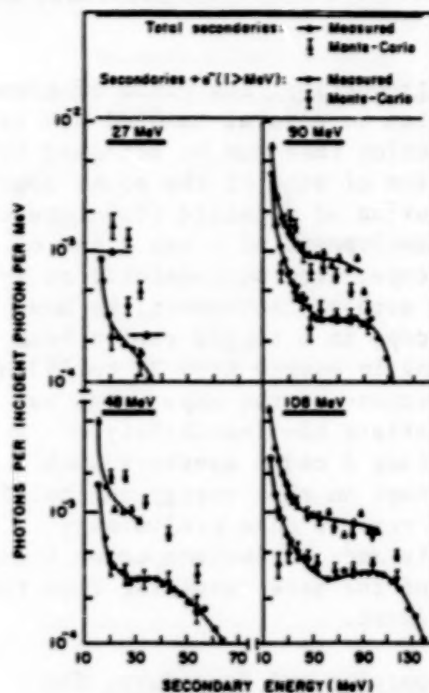
Fig. 3 Experimental and Monte-Carlo
secondary γ-ray spectra at various
incident γ-ray energies.

5. Acknowledgements. This work was supported by NASA grant NAGW-451 and
grants from the SERC.

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OPERATING CHARACTERISTICS OF A PROTOTYPE HIGH ENERGY GAMMA-RAY TELESCOPE

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1. Introduction. The field of gamma-ray astronomy in the energy range from ten to several hundred MeV is severely limited by the angular resolution that can be achieved by present instruments. The identification of some of the point sources found by the COS-B mission and the resolution of detailed structure existing in those sources may depend on the development of a new class of instrument (1). The coded aperture mask telescope, used successfully at X-ray energies (2), holds the promise of being such an instrument. We have operated a prototype coded aperture telescope in a tagged photon beam ranging in energy from 23 to 123 MeV. The purpose of the experiment was to demonstrate the feasibility of operating a coded aperture mask telescope in this energy region. This paper reports some preliminary results and conclusions drawn from some of the data resulting from this experiment.

2. Apparatus and Procedure. The apparatus is illustrated in figure 1. The incident beam passed through a mask, an anticoincidence counter, a position sensitive gamma-ray detector, a time-of-flight (TOF) counter, and a scintillation calorimeter. For the runs reported here, the mask consisted of an array of tungsten blocks, 6.3 millimeters square, arranged in a checkerboard pattern. The blocks were 2.7 radiation lengths thick and produced a spatial modulation of the beam that passed through the mask. The position-sensitive detector consisted of a stack of three drift-chamber modules.
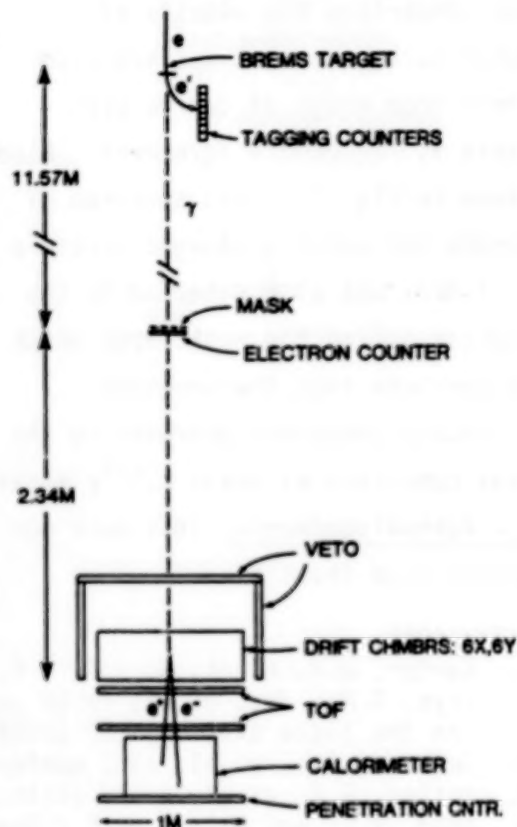
Fig. 1. Diagram of the apparatus.

Each module contained four drift chambers, two for measuring each of the two coordinates orthogonal to the beam. Photons converting in the drift-chamber array produced electron-positron pairs which passed through the remainder of the chambers and into the time-of-flight detector and the calorimeter. Readout of the chambers and calorimeter was initiated by a coincidence of a tagging count and the time-of-flight counters in the absence of a signal from the anticoincidence counter.

The experiment was operated in the low energy hall of the electron linac of the C.E.N. Saclay laboratory. A tagged bremsstrahlung beam was used as the source of photons. Eight tagging channels provided energy ident-ification of individual photons from 52% to 68% of the full electron energy. A signal from one of these tagging channels was required for readout of the experiment. Photon energy bands of 94-119, 78-99, 42-53, and 23-30 MeV were used. The assembly of chambers and associated scintillation counters and calorimeters could be rotated to permit data-taking at angles of incidence up to 40 degrees from the normal. The mask was rotated by the same amount during these runs.

The chambers had active areas of 85 by 85 centimeters. They had 9 millimeter gaps and 4 centimeter drift distances. No provision was made within the individual chambers to resolve the left-right ambiguity but chambers within one module were arranged in a staggered pattern so that the ambiguity could be resolved when observing reasonably straight tracks. The drift field was established by field planes which consisted of printed circuit boards each 1% of a radiation length in thickness on which the field-shaping electrodes had been etched. They were operated on an argon-isobutane mixture with a drift field of 1 kilovolt per centi-meter. Pulses from groups of chamber sense wires were discriminated and sent to a set of fast flip-flops which routed the logic pulses alternately to two time-to-digital converter (TDC) channels for each group. This permitted the recording of double hits on a sense wire as might be caused by the passage of a pair of tracks through the chambers. Pulse pair resolution was about 1 millimeter. The TDC's were operated in a CAMAC system which was controlled by a PDP-11/24 computer. TDC data for each reporting sense wire were recorded on magnetic tape along with the tagging channel, and pulse heights from the TOF scintillators and calorimeter.

Prior to the operation of the experiment at the electron linac it was determined that the chambers suffered from a loss of efficiency in the 25% of the drift space farthest from the sense wires. Using cosmic ray muons, it was found that individual track positions had a root-mean-square uncertainty of approximately 1 millimeter.

Following the data taking runs, the TDC data from the events were processed by a pattern recognition and track fitting program. From this came a list of positions of the conversion vertices of individual gamma rays. Approximately 25% of the triggers resulted in a conversion vertex appearing in the fiducial volume of the chamber array. The two-dimensional distribution of vertices could be matched to the checkerboard pattern of the mask. Vertex positions relative to the mask pattern were determined and aggregated to produce a plot of vertex density as a

function of distance across the shadows of the opaque and transmitting
mask elements. Figure 2 shows such a plot.
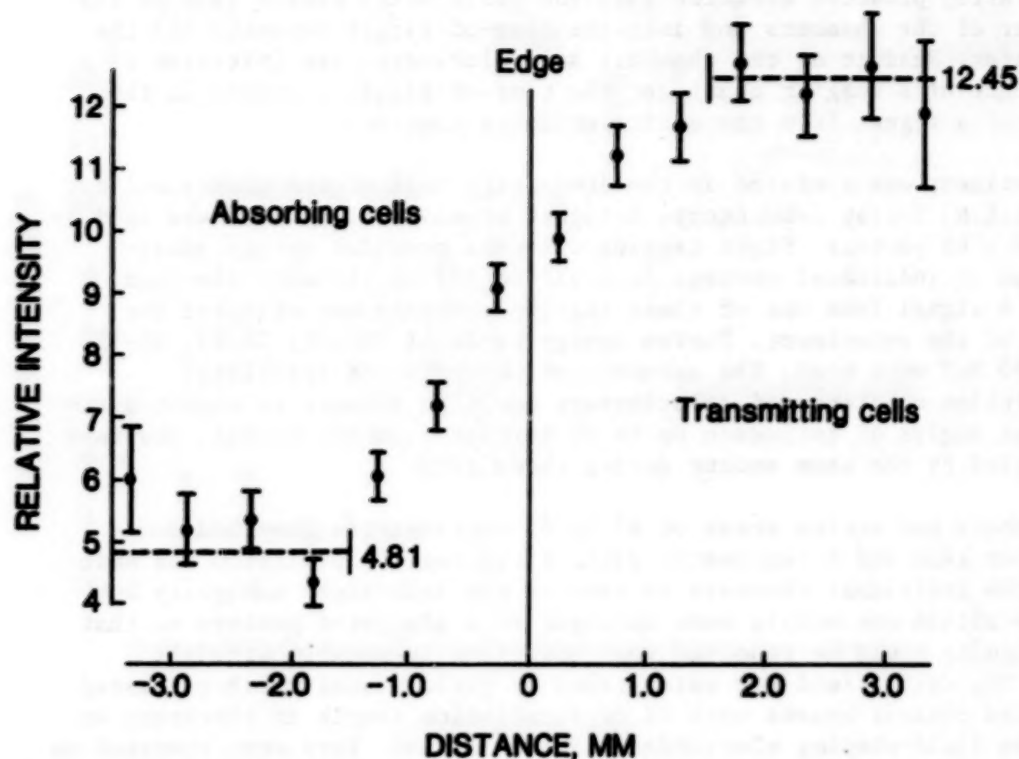
Fig. 2 Vertex density as a function of position within the shadows of
opaque (left) and transparent (right) mask elements. The case shown is
for 106 MeV photons at normal incidence.

3. Results. We refer to the ratio of vertex density behind the opaque
mask elements to that behind the transmitting elements as the modulation
ratio. This ratio should be simply the known transmission of the tungsten
elements at the photon energy in question. Except under the most
favorable conditions, this did not turn out to be the case. The table
below shows the modulation ratio for several of the runs and the
theoretical ratio.

The increase of the modulation ratio above the theoretical value could be
viewed as the result of the addition of a uniform background of events
which are not modulated by the mask. We attribute this uniform background
predominantly to a population of events that failed to be properly
recognized and fitted by the reconstruction program. The unexpectedly low
efficiency of the chambers and track error made it difficult, even with
manual scanning, to identify the track origins and trajectories with
certainty. This problem was exacerbated at low energies where scattering
of the tracks was greater. Supporting this supposition, a calculation in
which the chamber data were simulated by Monte Carlo methods shows that,
as chamber efficiency is diminished and track accuracy decreased, the
track recognition and fitting program fails to calculate the vertex

positions to about the degree observed. Furthermore, placing more
stringent requirements on the quality of the fit to the experimental data
produced a smaller sample of vertex positions but one which showed con-
siderably less of this uniform background. In the table, cases marked
with * were those to which this more stringent requirement was applied.
Approximately half the events met the requirement.

PHOTON ENERGY (MeV)	INCIDENT ANGLE (Degrees)	MEASURED RATIO	THEORET. RATIO	PHOTON ENERGY (MeV)	INCIDENT ANGLE (Degrees)	MEASURED RATIO	THEORET. RATIO
106	* 0	.287	.225	88	20	.632	.244
106	0	.405	.225	47	0	.598	.276
106	13	.557	.231	47	10	.718	.280
106	* 26	.536	.251	47	20	.751	.293
106	26	.653	.251	26	0	.737	.333
88	0	.474	.229	26	10	.669	.338
88	10	.614	.233				

The error in vertex location for events that were properly recognized can
be estimated from the width of the transition region between the shadows
of the opaque and transmitting regions. In the case shown in figure 2,
the vertex density makes the transition from 25% to 75% of full height
over a distance of 1.5 millimeters. If one were to model the vertex
position point spread function by a gaussian, this would imply an r.m.s.
uncertainty in vertex location of 1.1 millimeters. The table below shows
the vertex location accuracy and modulation ratio other energies and
angles.

4. Conclusions. We have demonstrated the feasibility of using a coded
aperture mask telescope at photon energies higher than used heretofore.
In this experiment, the reliability and accuracy of recognizing and
fitting tracks was not as great as would be needed for an astronomical
instrument. This condition could be improved by increasing the number of
chambers used and by improving the efficiency of the chambers.

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AN EXPERIMENTAL ASSESSMENT OF THE IMAGING QUALITY OF THE LOW ENERGY GAMMA-RAY TELESCOPE ZEBRA.

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ABSTRACT

One gamma-ray detection plane of the ZEBRA telescope, consisting of nine position sensitive scintillation crystal bars designed to operate over the spectral range 0.2 to 10 MeV, has been constructed in the laboratory. A series of experimental images has been generated using a scaled down flight pattern mask in conjunction with a diverging gamma-ray beam. Point and extended sources have been imaged in order to assess quantitatively the performance of the system.

1. INTRODUCTION. The balloon-borne low energy gamma-ray imaging telescope ZEBRA is designed to operate in the spectral range 0.2 - 10 MeV. A detailed description of the telescope configuration may be found elsewhere (1). It consists of two independent detection modules mounted on either side of a three axis gimbal system. Each module comprises a position sensitive detection plane (PSD) of 9 Sodium Iodide scintillation bars, each of dimensions 5.8cm x 5.0cm x 55cm, with 13 similarly sized non position sensitive bars for anticoincidence purposes. At a distance of 3.5 metres in front of this plane is situated a coded aperture mask, constructed out of Tungsten alloy elements arranged in a 2 x 2 mosaic of a 9 x 7 Uniformly Redundant Array (URA) pattern (2). The intrinsic angular resolution of the device is governed by the angle subtended by a mask element at the detection plane. For the ZEBRA telescope this amounts to

~1° x ~1° . The point source location accuracy, however, is determined by the positional resolution of the detection plane and the strength of the detected source. For this reason, the bars in either detection module are mounted orthogonally in order to symmetrise and optimise this parameter.

The position sensitive detection bars have been studied carefully in the laboratory environment in order to fully assess their imaging capabilities. The initial tests were performed on single bar imaging systems (3), extending later to experimental systems of several bars operating in conjunction to provide two dimensional data.

In the last few months, a full ZEBRA PSD of nine bar units has been assembled in the laboratory and a series of experimental images has been generated. The arrangement consisted of the 9 bar plane in front of which, at a distance of 2.5 metres, a half-size 9 x 7 pattern mask was aligned so as to be perfectly parallel. This configuration naturally leads to the imaging system being 'focussed' on a source plane a further 2.5 metres from the PSD. Signals from the 18 photomultiplier tubes were digitised by two ADC's and stored on magnetic tape via a PDP 11/24 computer, subsequent analysis being performed on an HP 1000 computing system.

Two types of source distribution were studied: point sources, both single and multiple, and extended sources artificially contrived by continuously moving a point source during the integration period. For these laboratory experiments a preliminary calibration of the detection plane was performed by means of a collimated source (Cs.137 ~662 keV) placed very close to each bar in succession at three well determined positions along the length. An energy look-up table was also calculated for each bar in order to provide a uniform spectral response both down the length of the bars and between the entire set.

2. EXPERIMENTAL IMAGES.

a) Point Sources. A 100 μC Cs 137 source was employed as the object to be imaged. At a distance of ~5 metres the counting rate was found to be ~15% of the integerated background event rate. The source was placed in over 80 well defined positions across the object plane and images accumulated for 10**5 events (i.e. about 1.5 x 10**4 source counts). For the purposes of analysis, an energy window around 662 keV was established such that only events under the Cs energy loss photopeak were accepted.

The data were binned in 128 energy bins of which 112 corresponded to the active region of the bars (the central 49cm), thus the shadow of one mask element covered 16 pixels. A straightforward correlation analysis (4) of the 9

x 112 data set and the 9 x 7 mask pattern allowed reconstruction of the source distribution. A typical example of the many images obtained is shown in Figure 1.
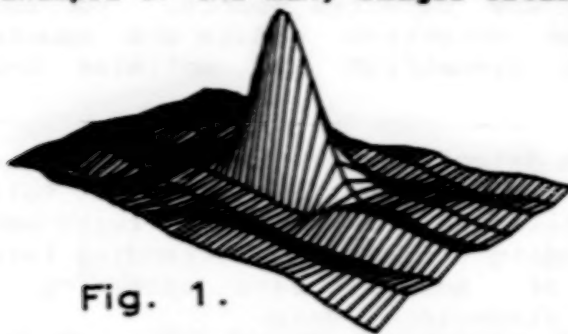
Fig. 1.

The triangular point spread function intrinsic to this decoding method is readily apparent. In this image there are ~5 x 10**4 source counts and ~3 x 10**4 background events. The full width at half maximum of the peak is 16.45 +/- 0.13 channels in comparison to the theoretical minimum of 16. The larger figure is due to the finite positional resolution of the detection plane and mechanical errors in setting up the experiment.

Figure 2. shows the reconstructed peak positions obtained from 6 images in comparison to the true source positions, the data being expressed in arcminutes from the centre of the field of view. The line is a weighted least sqares fit to the experimental data. The error bars are 1 sigma, and it can be seen that the two sets of data are in excellent agreement.
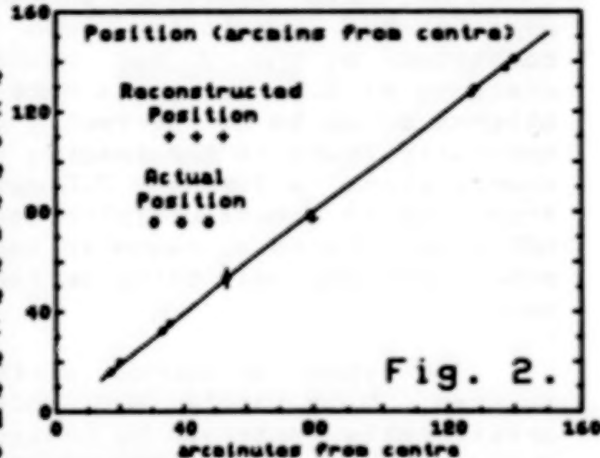
Fig. 2.
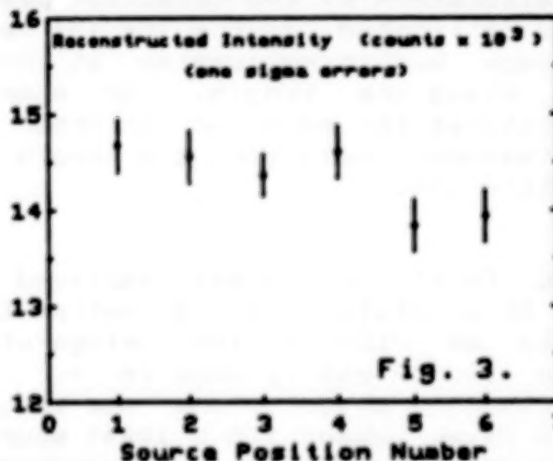
A slight magnification mismatch is evident, probably due to difficulties in employing a diverging gamma-ray beam and the subsequent need to measure mask/source and mask/PSD distances very accurately. The reconstructed intensity at each position is shown in Figure 3. Some very slight reduction in intensity for more off-axis sources is apparent. This is due to a combination of the cosine effect, self vignetting by the body of the mask and the reduced apparent integral thickness of the detection plane (5,6).

Fig. 3.

The point source location accuracy as a function of signal to noise ratio (SNR) is depicted in Figure 4. The two scales on the X-axis reflect the different values which

may be attributed to the variance of the background, either with or without accounting for systematic structure.

Fig. 4.
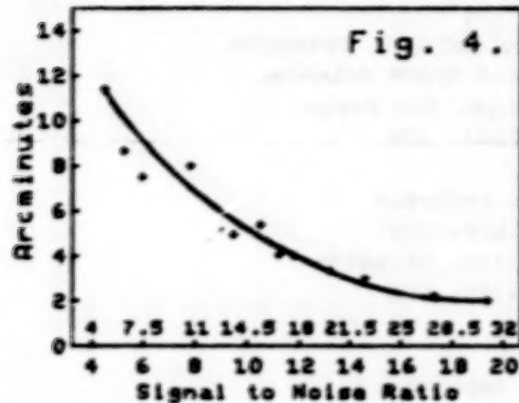
b) Extended Sources. In order to simulate an extended source, a point source was made to rotate within the field of view. Several images were accumulated for different radii. Figure five depicts such a source with a radius of 20 cm ($\sim 2°$). The centre of the distribution falls to the background level as expected. Analysis of the extended source distributions is continuing.

3. CONCLUSIONS This paper presents the first two dimensional images to be obtained using one full ZEBRA detection PSD. Using only preliminary laboratory calibration procedures, and making no allowance for non-uniformities in the background event rate (such as background subtraction) it has been demonstrated that high quality images may be obtained. The point source location accuracy is at the arc minute level.
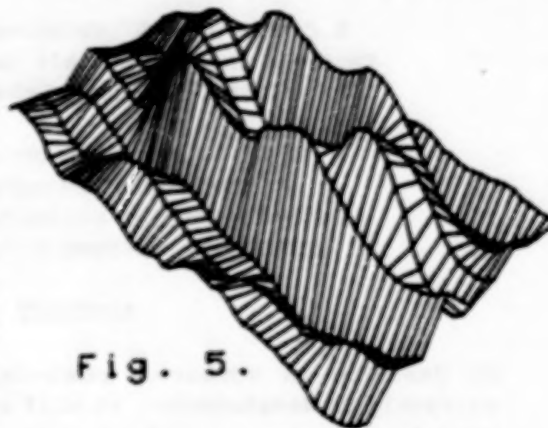
Fig. 5.

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ADVANCED TECHNIQUES FOR HIGH RESOLUTION SPECTROSCOPIC
OBSERVATIONS OF COSMIC GAMMA-RAY SOURCES

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ABSTRACT

We describe an advanced gamma-ray spectrometer that is
currently in development. It will obtain a sensitivity of <
10^{-4}ph/cm^2-sec in a 6 hour balloon observation and uses
innovative techniques for background reduction and source
imaging.

1. <u>Introduction</u>. Over the past decade gamma-ray spectrometers have
achieved sensitivities of 10^{-4} to 10^{-3}ph/cm^2-sec to steady sources. This
has lead to the discovery of gamma-ray line emission and narrow band
continuum structure in the spectra of a wide variety of objects and
phenomena [1], e.g. the galactic center, X-ray pulsators, the Crab pulsar,
gamma-ray bursts and transients, and solar flares, the interstellar medium
[2] and SS433 [3]. In spite of the impressive observational progress, it
is generally true that line emission has been detected from only the
brightest sources. The discovery of fainter sources and detailed study of
the brighter ones requires factors of 10 to 100 sensitivity gain [4]. This
is only practical with much lower background instruments than are
available today. The goal of the collaborative program described here is
to develop an instrument that has much lower background per unit area and
is an order of magnitude more sensitive per unit observing time than
present instruments. This will be used for observations of isolated
sources and complex source fields from balloons at a sensitivity of <
10^{-4}ph/cm^2-sec, and its techniques will be applicable to future
instruments carried in space, where < 10^{-5}ph/cm^2-sec could be achieved.

Instrumentation. The instrument, shown in Figure 1, contains an array of twelve 5.5 x 5.5 cm, coaxial, n-type Ge detectors. These have an energy resolution of 1.4 (<0.6) keV at 511 (<100) keV, a total area of ¯ 300 cm^2 and operate from 10 keV to 10 MeV. They are contained in a single cryostat that has very high thermal efficiency, allowing 80 hours of operation with a 10 liter LN$_2$ Dewar. This is surrounded by anticoincidence shield made of 5 cm thick BGO at the sides and rear and 10 cm thick CsI at the front. Apertures in the latter define a 19° FWHM field of view. The instrument has 3 operating modes, or configurations, which result from the use of additional collimation components. (a) The "Source Mode" uses a 3° FWHM passive collimator which is optimized for observations of discrete sources at known positions. (b) The "Image Mode" uses an optimum coded modulator to observe complex source regions by imaging a 12° FWHM field with 2.5° angular resolution (c) In the "Diffuse Mode" the 19° FWHM aperture is left clear in order to maximize the sensitivity to diffuse sources. The instrument mass is 450 kg.

The detectors use dual electrical segments and pulse shape discrimination to distinguished between Compton scattered gamma-rays, which are multiple site interactions, and β-decays which are essentially single site [5]. The latter are the dominant background component from a few hundred keV to > 1 MeV in heavily shielded Ge instruments [6,7,8] and represent a fundamental obstacle to sensitivity improvements. Their elimination is a major goal of this program. Gamma-rays < 200 keV are mostly detected in the 1.5 cm thick front segment. Higher energy gamma-rays are mostly detected as a coincidence between the two segments or a multiple site event in the rear, 4.0 cm thick, segment. The latter is possible because the detector's finite charge drift velocity results in a sharp (broad) charge pulse for single (multiple) site events which is sensed by a pulse shape discriminator. This rejects > 95 percent of the single site events while accepting >80 percent of the multiple site events.

Imaging is achieved through the use of the optimum coded modulator. This produces temporal aperture modulation that is mathematically equivalent to the better known spatial aperture modulations [9]. It consists of 63 opaque and transparent moving elements which are located ¯ 200 cm above the detectors and modulate the flux from gamma-ray sources. The resulting moving shadowgram produces temporally modulated counting rates in the detectors, from which a 2-dimensional, sidelobe-free gamma-ray image is deconvolved. The modulator elements, made of BGO with PIN photodiodes, operate in anticoincidence with the detectors.

The anticoincidence shield is primarily made of BGO, which offers greater attenuation per unit shield mass than CsI or NaI and also results in a more compact shield due to its high density, 2 times that of NaI. However, the low light output of BGO necessitates good PMT light collection in order to achieve a low anticoincidence threshold, < 100 keV. Therefore the shield will use ¯ 50 separate BGO elements, based on a nominal 5 x 7 x 21 cm size, each with its own PMT.

2. Background and Sensitivity. The background is shown in Figure 2 and the sensitivity for a 6 hour balloon observation is shown in Figure 3. At 1 MeV the background is 0.14 and the detector volume is 11.5 times that of the
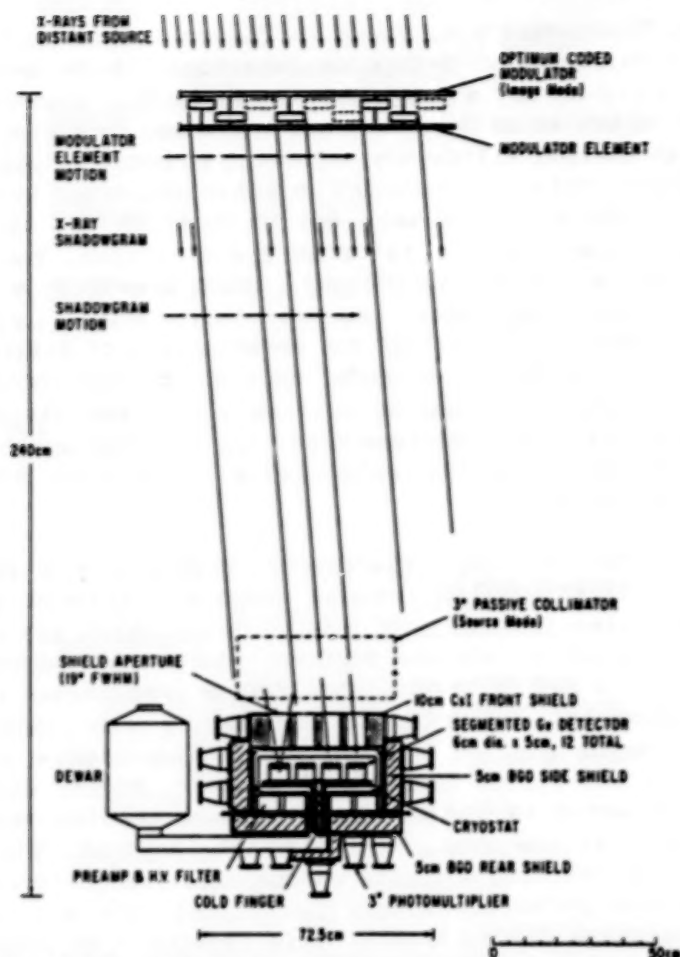
Figure 1. The high reduction gamma-ray spectrometer contains an array of 12 coaxial Ge detectors surrounded by a BGO and CsI anticoincidence shield. A cross section is shown of the optimum coded modulator, which is located 200 cm above the detector and used for imaging observations.

most sensitive contemporary instrument [10,11] resulting in a sensitivity improvement per unit observing time that is a factor of 9 (= 11.5/0.14). The detectors' superior energy resolution results in an additional sensitivity gain of a factor of ~ 1.5 below ~ 500 keV.

4. Program Status and Plans. The detector, shield and modulator concepts have been proven in extensive laboratory tests. In the fall of 1985 a test balloon flight of a single, heavily shielded detector will be performed. The 8 cm thick CsI shield will reduce the gamma-ray leakage to a point where rejection of detector radioactivity can be clearly seen. It is planned to conduct the first scientific observations with the complete instrument in the fall of 1987.

ORIGINAL PAGE IS
OF POOR QUALITY

SOURCE MODE BACKGROUND

A - APERTURE
L - LEAKAGE
R - RADIOACTIVITY
T - TOTAL

FRONT
SEGMENT →

REAR PSD
+
FRONT-REAR
COINCIDENCE

COUNTING RATE (COUNTS / cm² - sec - keV)

ENERGY (keV)

NARROW LINE SENSITIVITY

IMAGE MODE ◇
SOURCE MODE ▽
DIFFUSE MODE ○

3σ MINIMUM DETECTABLE FLUX (PH cm⁻¹ s⁻¹)

ENERGY (keV)
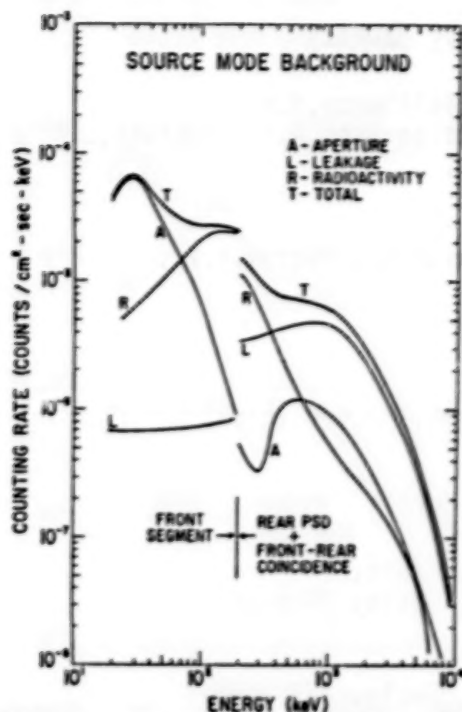
Figure 2. The Source Mode background components are shown for the different gamma-ray acceptance modes of the detectors. The 3° collimator results in a small aperture flux which is ~ 20 times greater below 300 keV in the Image Mode. A 98 percent rejection of detector radioactivity at 1 MeV is assumed. Such a reduction would allow a 10 times further reduction in the total background of future instruments through the use of a thicker anticoincidence shield.

References

Figure 3. The sensitivity to narrow lines is shown for a 6 hour balloon observation. The increase below ~ 50 keV is primarily due to decreasing atmospheric transmission. Differences among the observing modes are due to different backgrounds and source modulation efficiencies. Carried in space with a 10 cm BGO shield, this instrument could achieve an Image Mode sensitivity of 10^{-5} ph/cm²-sec over most of its energy range in a 7-day observation.

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THE GAMMA-RAY TELESCOPE GAMMA-1

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ABSTRACT

French and Soviet specialists have designed and
built the gamma-ray telescope GAMMA-1 to detect
cosmic gamma rays above 50 MeV. The sensitive area
of the detector is 1400 cm^2, energy resolution is
30% at 300 MeV, and angular resolution 1.2° at
300 MeV (and less than 20'arc when a coded aperture
mask is used).Results on calibration of the qualifi-
cation model and Monte-Carlo calculations are presented.

1. Introduction. SAS.II, then the long-lived COS-B, have shown the
interest of high-energy gamma ray astronomy. Numerous point sources
have been found, but identification with physical objects has been
possible for only a few of them. The first objective of the GAMMA-1
experiment was to increase the sensitive area, and lower the angular
resolution of a gamma ray detector. A wide gap spark chamber, tested
at DESY in 1976 (1,2), showed that it was possible to obtain
better than 2° angular resolution with this technique.

However, in order to still increase this resolution, a model of
coded aperture mask was developped (3). In a spark chamber, image
deconvolution is performed not only by position detectors,but also
by taking into account the rough (<3°) arrival direction information.
The addition of this mask, and the complexity of the experiment itself,
resulted in some delay over the initial launch date.

2. The experiment. The Gamma-1 telescope is illustrated on Fig.1. The
main detector is a 50X50 cm ,12-layered wide gap spark chamber. It is
shielded with lateral and upper anticoincidence,inside and outside the
satellite skin. A time of flight (SV + SN) can veto upgoing particles,
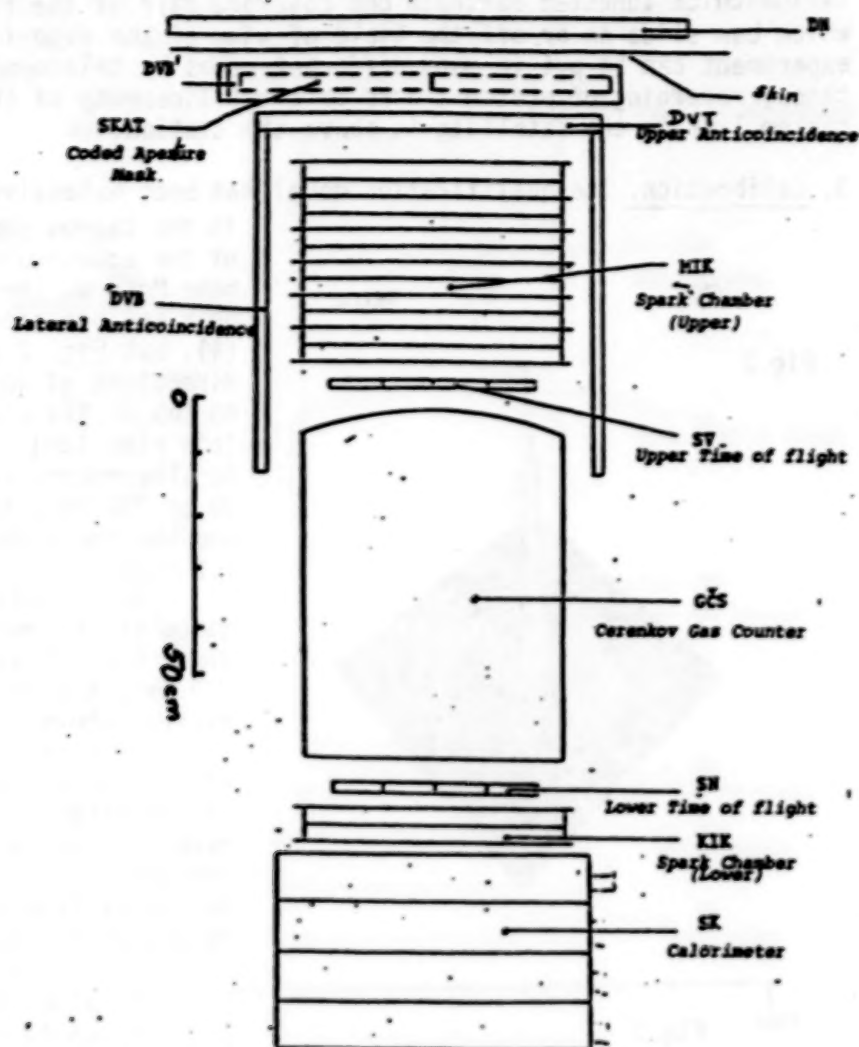
Fig. 1

THE G A M M A - 1 EXPERIMENT

in reduddance with a Cerenkov gas counter. A two layered spark chamber below the SN counter is helpful when the very high energy electron-positron pair cannot be separated in the upper chamber.

To measure the energy, scattering is used from 50 to 200 MeV, and a four-layered-calorimeter is used above 100 MeV.

The spark images are viewed through an optical system by two orthogonal vidicon cameras and digitised before storage on a recorder. The 50 cm width of the chamber is divided in 4096 points (localisation accuracy 0.125 mm). For each spark, there are three lines of sweep, separated by 17 mm; the width of each digitised spark is also recorded.

The dead time of the high voltage (24 KV) generator is less than 0.5 sec. Data from the vidicons, and from all counters, along with housekeeping informations, are dumped to the telemetry station twice a day.

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OG 9.2 - 10

The coded mask is made of two orthogonal one-dimensionnal arrays of 1cm-thick tungsten bar,each one covering half of the field of view, which can slide on or off the field of view of the experiment. The experiment can be put in many different modes by telecommands(for instance, recording of proton tracks to check linearity of the imaging system.) while the satellite is above the station.

3. Calibration. The qualification model has been extensively calibrated in the tagged gamma ray beam of the accelerator "Pakhra", near Moscow. The set-up of the beam has been described elsewhere (4), but Fig. 2 shows arrival directions of 1000 gamma rays on top of the chamber, on axis (bin size 1cm). FWHM is about 4cm.The energy resolution, from 30 to 700 MeV, is about 30 MeV, and the openning of the beam 2.5 mrad.

In parallel, Monte-Carlo calculations were performed, to check the actual response up to 700 MeV, and to be used as calibration above.

Figures 3 and 4 show the efficiency and angular resolution of the detector,without the coded mask. Energy resolution (as measured by the calorimeter), decreases from 95% at 50 MeV to 30% at 500 MeV.

Calibrations have also been performed using the mask. An exemple of correlation function at 300 M eV is given in Fig. 5. Bin size is 5' arc. The actual position of the beam was at -15'. Reconstructed direction is (-10 ± 5)' arc, with a FWHM of 28'.

Such a figure may seem high, but when one takes into account the angular width of the beam itself, the FWHM is less than 15' of arc.

C300   THETA=0

Fig.2

Fig.3

Monte-Carlo
simulation

Accelerator
Data

ENERGY (MeV)

Fig. 4
Angular Resolution

ENERGY (MeV)

Fig. 5
Correlation Function

COUNT / BIN

5' BIN NUMBER

INCIDENCE ANGLE (DEGREES)
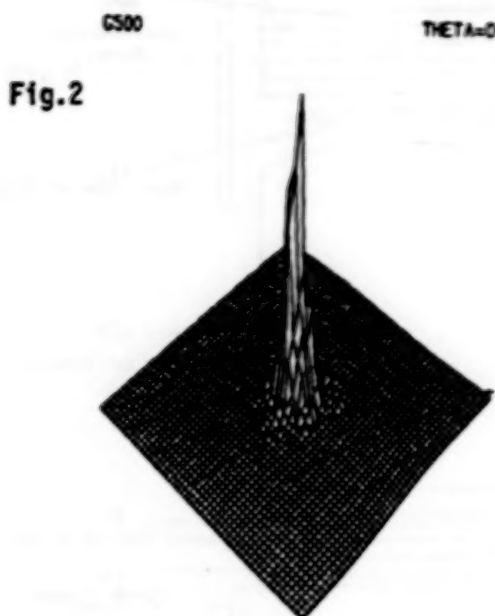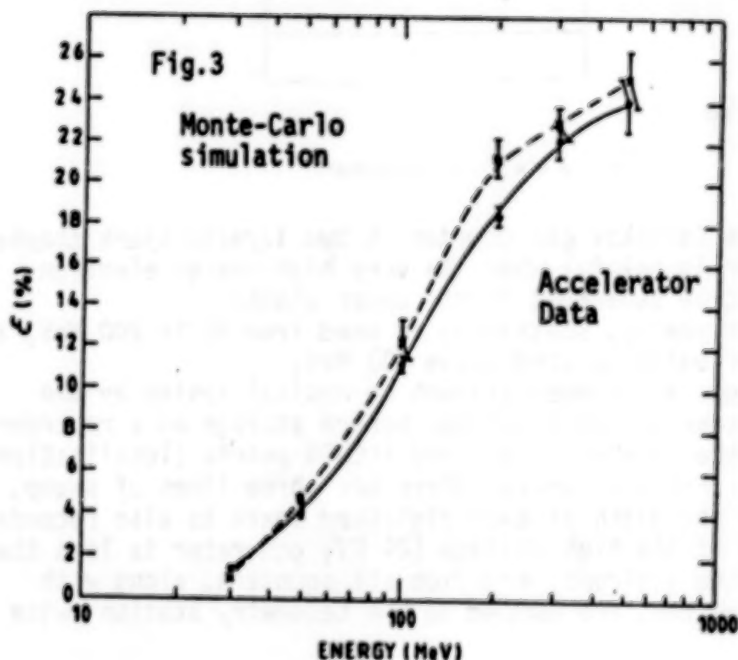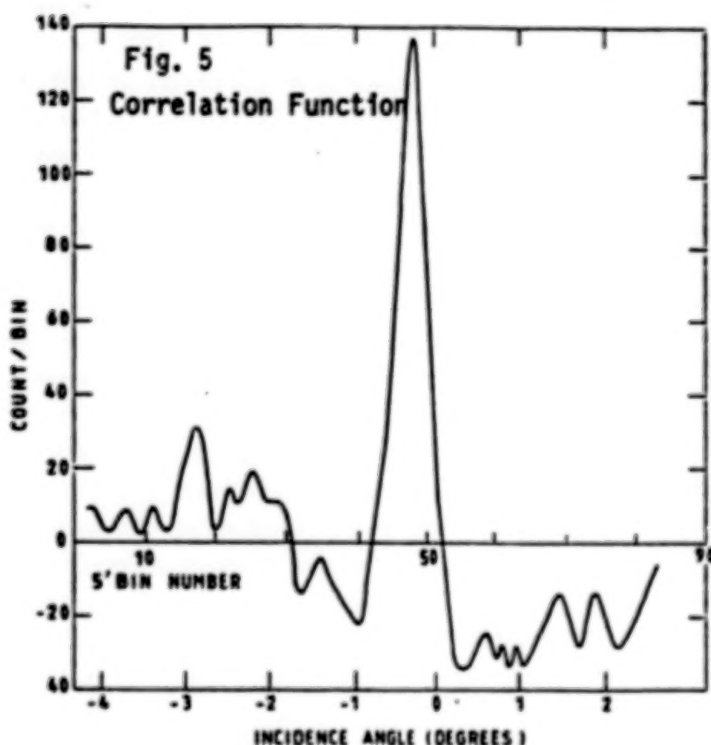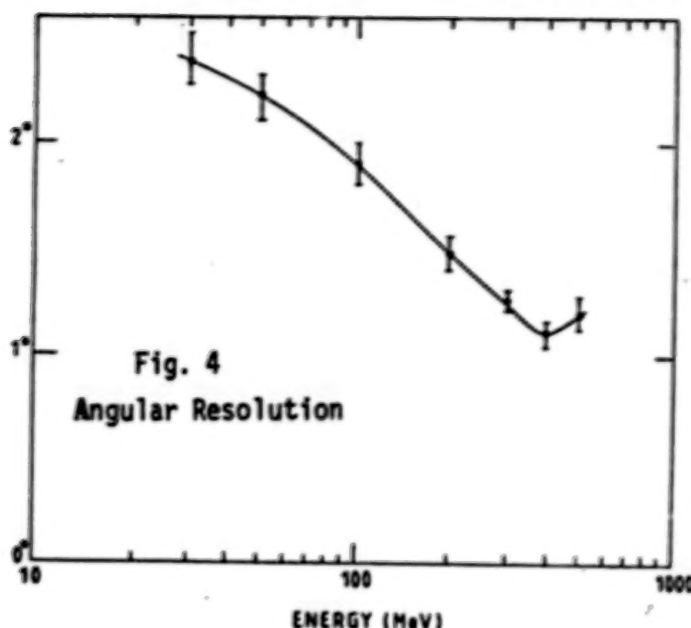
4. Conclusions. The calibrations performed on the qualification model of the Gamma-1 experiment , as well as calculations, have shown its potential in reconstructing gamma-rays directions. The use of a coded mask can give images with 15' arc resolution. Absolute celestial coordinates are obtained with the help of a stellar sensor with 5' arc accuracy.

Without the mask, upper flux limits of 10^{-7} should be detected within two weeks of exposure, using a sensitive area of 1400 CM^2 , and gamma rays within 10° of the axis.

Calibration of the flight model will be performed at the end of 1985, on a reduced program. Then, it will be integrated in a Salyut-type, 3-axes stabilised, satellite, to be launched in late 86 on a low-altitude orbit.

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THE FIGARO EXPERIMENT FOR THE OBSERVATION OF TIME MARKED SOURCES IN THE LOW ENERGY GAMMA-RAY RANGE

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1. **INTRODUCTION.** The only two firmly identified galactic γ-ray sources in the second COS B catalogue (1) are the pulsars PSR 0531+21 (Crab) and PSR 0833-45 (Vela). Their spectra are rather similar in the medium energy γ-ray band, but differ drastically at lower frequencies. In the region between 100 keV and 10 MeV the detailed shape of the emission is particularly important, since one expects a turn-off which is related to the geometry of the source (2). A marginal evidence of such a turn-off just below 1 MeV has been reported for the Vela pulsar by Tümer et al. (3).

In order to study sources with a well marked time signature in this energy band, we have specifically designed the FIGARO - French Italian GAmma Ray Observatory - experiment (4), whose first version was launched in November 1983 from the Sao Manuel base (Brazil), and was destroyed in a free fall following a balloon burst at an altitude of 50 mbar. The available portion of the growth curve and the calibration data demonstrate that the effective area and the noise figure (extrapolated to the float altitude) were in accordance with the project goals, and indicate that the required level of sensitivity can indeed be reached (5).

In this contribution we give a brief description of the new improved version of the experiment, FIGARO II, which is nearly completed and whose launch is scheduled before summer 1986.

2. **DESCRIPTION OF THE EXPERIMENT.** FIGARO II is a wide angle γ-ray detector with a total geometric area of 3600 cm^2

of NaI(Tl), 50 mm thick. It is actively shielded from the
atmospheric background by a lateral wall of NaI(Tl) tiles
(25 cm high, 70 mm thick), and by a lower array of plastic
scintillator blocks having a grammage of 50 g cm^{-2}. At vari-
ance with the first version, the main detector is square in-
stead of rectangular, providing a more favourable ratio area
vs weight; the lateral wall is higher by 5 cm; and the photo
multiplier tubes of the nine detector elements are reversed,
embedded within the bottom plastic, so as to have a field
of view free of passive material, and to extend to lower
energies the accessible spectral band.

The reduction of the geometrical area by about 13% does
not affect appreciably the sensitivity of the experiment:
in fact, it is very nearly compensated by the increased ef-
ficiency achieved with the PM's reversal, and by the lower
noise contributed by the calibration source. In the new
version, the gains of the individual detector elements are
monitored with 511-keV photons from a very weak positron
source (Na^{22} of about 40 nCi of activity), tagged by the
companion photons emitted in the opposite direction, and
detected on a small BGO crystal. An upper plastic shield 5
mm thick is used to anticoincide low energy charged parti-
cles. A schematic view of the complete payload (but not the
BGO detector of the tagged source) is shown in Fig. 1.

Data from the nine detector elements are analyzed by a
single 8 bit A/D converter, if there are no veto signals
from the various anticoincidence sets. The anticoincidence
window depends on the pulse height, and can be varied by
telecommand. Qualified events are transmitted individually
with a time resolution better than 0.05 ms; they are also
cumulated onboard into 10 counters, and transmitted on a
different telemetry channel every 2 ms. Signals which are
tagged by a coincidence with the BGO crystal are sent sepa-
rately, and analyzed in order to monitor continuously the
gains of the individual amplifiers; these are corrected and
equalized by telecommand, so that only one channel of A/D
conversion is needed.

3. <u>EFFECTIVE AREA AND SENSITIVITY</u>. With respect to FIGARO
I, this second version can be flown profitably at lower al-
titudes, with a safer heavy-load balloon, because of the im-
proved performance at the lower end of the spectral window;
furthermore, the spectral capabilities have been significant-
ly increased with the adoption of the A/D converter. Both
changes have been warranted by the low counting rate demon-
strated by the Brazil flight.

On the other hand, the most critical experimental solutions have remained unchanged, so that we feel confident in modelling FIGARO II with the Monte Carlo code used successfully so far. Fig. 2 shows the total ($\blacktriangle$) and photopeak ($\blacktriangledown$) effective area at a float altitude of 5 g cm^{-2} of residual pressure. The estimated sensitivity to a pulsed continuum, attainable in a five hour pass during a transmediterranean flight is reported in Fig. 3 for the same residual pressure; the numerical modelling of the γ-ray atmospheric background used in this computations has been described in detail elsewhere (6).

Apart pulsars, which remain our main target, all time-marked sources in this energy band such as hard-tail X-ray pulsators, solar flares and γ-ray bursts can be observed with a very high sensitivity by this experiment. For the γ-bursts, in particular, it will be very interesting the search for decaying periodicities during the event.

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FIG.1
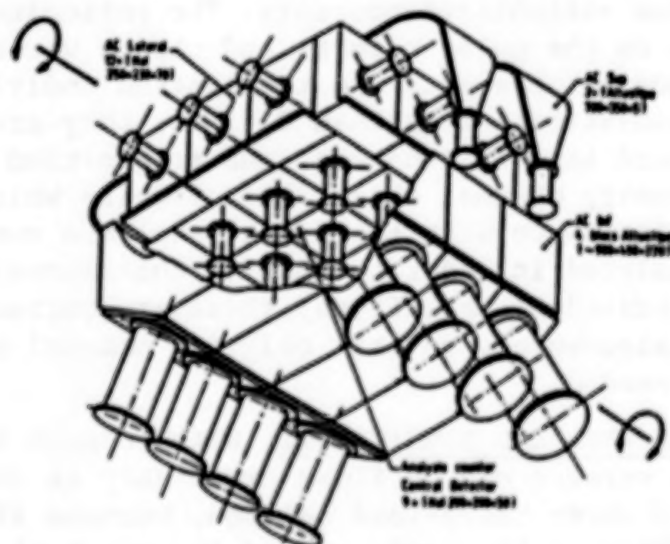
Fig. 2

3σ sensitivity
5 g cm⁻² res. atm.

PSR 0531+21

Fig. 3

N85-34951

OG9.2-12
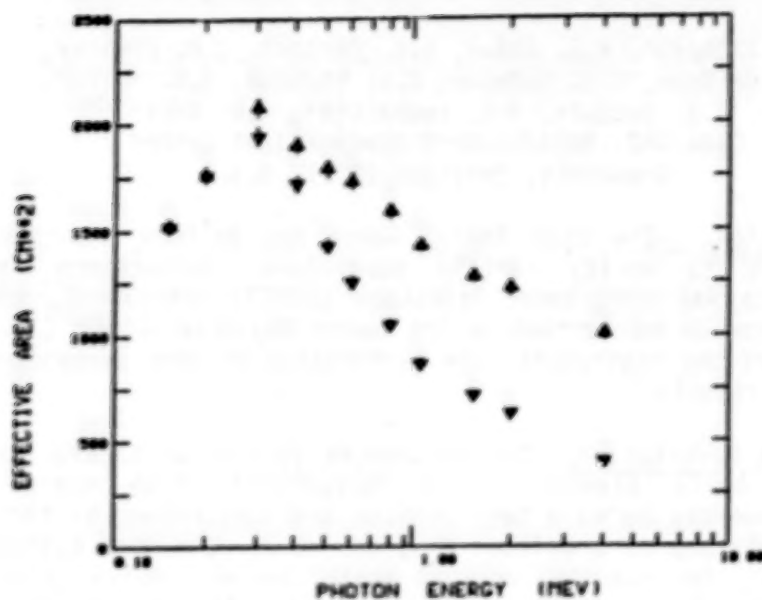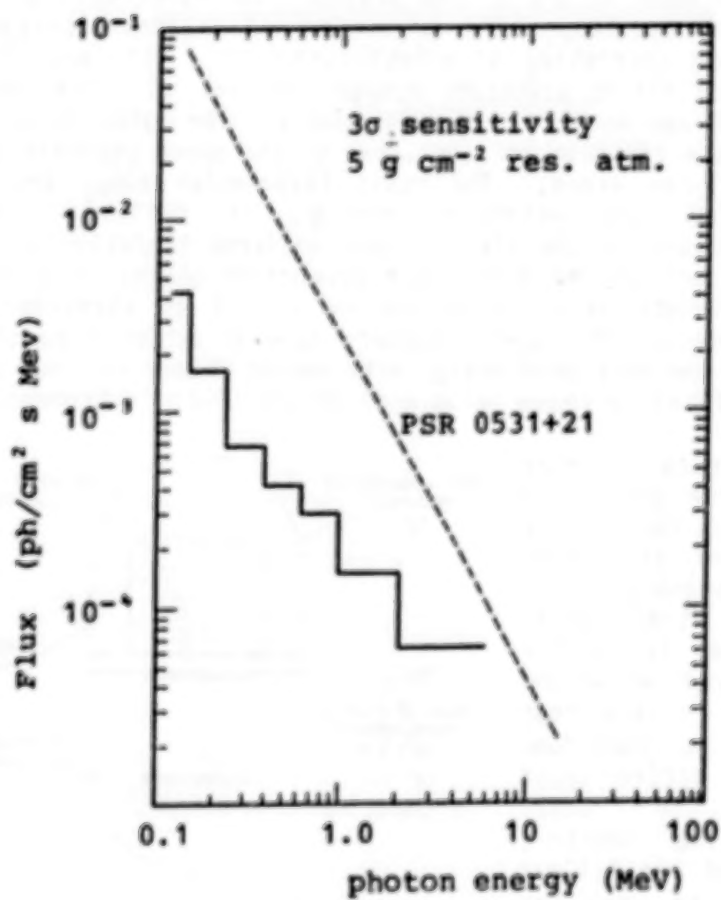
HIGH ENERGY GAMMA RAY BALLOON INSTRUMENT

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1.   Introduction.   The High Energy Gamma Ray Balloon Instrument was built in part to verify certain subsystems' performance for the Energetic Gamma Ray Experiment Telescope (EGRET) instrument, the high energy telescope to be carried on the Gamma Ray Observatory (1). This paper describes the instrument, the performance of some subsystems, and some relevant results.

2.   Instrument Description.   The instrument is similar in size to EGRET and has the basic elements of a conventional high energy γ-ray telescope. However, being a test vehicle and constrained by the weight and cost limitations of a balloon program, it is much more austere than EGRET. It has, for example, only 12 spark chamber modules (Figure 1), compared to the 36 on EGRET. A γ-ray entering from above produces no signal in the anticoincidence scintillator "A", but may convert to an electron-positron pair in one of the plates interleaved with the upper 10 spark chamber modules. The electron and positron trigger the coincidence system consisting of scintillators "B", "C", and "D" with the proper time of flight signature between "B" and "C". The inclusion of the "D" signal was optional and commandable. The coincidence signal is used to initiate the high voltage pulse to the spark chambers and the readout of the γ-ray event. The basic information about the γ-ray, arrival direction and estimated energy, is derived from the reconstructed picture of the electron and positron trajectories in the spark chamber. Each of the eight pair production plates is a sheet of 0.08 radiation length lead, supported on a grid of stretched high-strength steel wires. The spark chambers have an active area of 81 cm by 81 cm, are of the wire grid design with magnetic core readout and are essentially identical to those being used on the EGRET instrument.

The anticoincidence counter consists of three pieces of scintillator which form a five sided box around the upper spark chamber assembly. The placement of the anti-coincidence system inside the pressure vessel reduces weight and is far less costly than the machined and polished dome surrounding the entire upper portion of the EGRET instrument. The shorter, modular design of the balloon anticoincidence is not as effective as the monolithic dome and it therefore

Figure 1 -- Schematic diagram of the High Energy Gamma Ray Balloon Instrument

represents a more severe test of its ability to screen out unwanted events.

The "B" and "C" parts of the triggering system each consist of an array of 16 scintillator tiles in a 4 by 4 pattern. Each tile has its own light pipe and phototube. This coincidence system serves two purposes: (1) The allowed combinat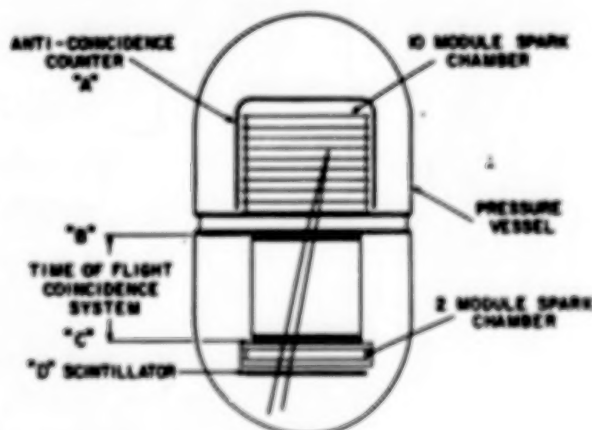ions of "B" and "C" tiles define the instrument aperture. (2) These scintillator planes are operated in a time-of-flight arrangement which requires that the particles pass through the "B" plane before the "C" plane, i.e., they must be downward moving. The performance of this coincidence system is discussed in Section 3. The EGRET coincidence system uses the same 4 by 4 scintillator arrays and an almost identical time-of-flight electronics system. The "D" detector is a single unit of plastic scintillator which may be used to verify that at least one of the particles penetrates the entire detector.

The active detectors are contained in a pressure vessel made of aluminum honeycomb with Kevlar face sheets. This composite vessel is lightweight and low density (area density less than 0.5 g cm^{-2}) yet capable of being evacuated to remove contaminants. The upper portion of the vessel and the lower spark chamber area are filled with a spark chamber gas mixture (98.5% neon, 0.75% ethane, 0.75% argon), while the region containing the coincidence scintillator, phototubes, and electronics is filled with air. The active area is approximately 6560 cm^2 with an area efficiency factor of about 1800 cm^2 (E> 400 MeV) The instrument size is 3 m by 1.6 m diameter. With its gondola, it weighs 1300 kg. Balloon flights which provide the results reported here were launched from Palestine, Texas.

3. Relevant Subsystems.

a. Spark Chamber. The individual modules have 992 wires in each plane, giving a positional resolution of about 0.4 mm for spark location. The modules are made entirely of low-outgassing materials with the beams themselves being made of Macor. An extensive effort was made in developing techniques for stacking, holding, and determining the alignment of the spark chambers, so that the absolute pointing direction of the assembly could be determined with high precision. The use of a set of optical refererences allowed the absolute pointing direction to be determined to an arcmin. The techniques which have been used in the EGRET development are a direct successor. The performance of the spark chambers is seen in Fig. 2, which shows the electron-positron pair resulting from a high energy γ ray interaction. The vertical scale has been compressed in the figure by a factor of 4.7.

b. Time-of-flight coincidence system. The time-of-flight measurement is an important discriminator against unwanted triggers. Each of the 32 tile signals from the "B" and "C" arrays is sent to a constant fraction discriminator. The discriminator signals are summed for each array (with propagation times matched). The time difference between the total "B" signal and the total "C" signal is then digitized using a circuit similar to previous experiments (2). With a 75 cm separation, the time difference between upward-moving and downward-moving particles is 5
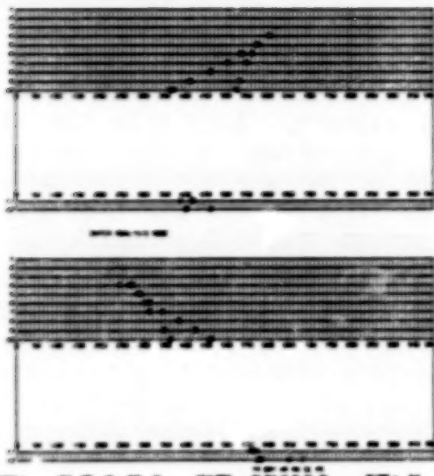
Figure 2 - Orthogonal views of a γ-ray pair production event in the spark chamber.

Figure 3 - Time of flight histogram for neutral events during one balloon flight.

nsec. The acceptance threshold for the time difference is adjustable by command. The discrimination, summation, digitization, and comparison is completed in about 400 nsec and is included in the trigger signal to the spark chamber. A histogram of the time-of-flight measurements is accumulated in the data system and regularly telemetered to the ground station. A sample histogram for neutral events, taken directly from the Ground Support Equipment display, is shown in Figure 3. The peak to the right represents downward-moving γ rays and is well separated from the upward-moving peak to the left.

c. Anticoincidence System. As noted in Section 2, the anticoincidence scintillator on the High Energy Gamma Ray Balloon Instrument does not surround the upper layer of the time-of-flight coincidence system, in contrast to other instruments such as SAS-2, COS-B, and EGRET. This short anticoincidence system was recognized as a negative design aspect, because horizontal or even partially downward moving particles could interact above the upper layer of the coincidence system and produce a downward moving particle within the instrument aperture.

An approximate model of predicted event rates was developed from the data of SAS-2 and tested on previous balloon instruments. When applied to the geometry and material factors of this instrument, this model gave the predicted rates which are shown in Table 1, which also shows the observed event rates during a balloon flight. The model did not take into account the different characteristics of this anticoincidence system from all the others.

The overall agreement between the predicted and observed event rate is an indication that the short anticoincidence system was not a major limitation of the instrument. The differences in the types of events seen is probably in large part the result of the anticoincidence configuration, for which no correction was made in the model. The fraction of events which are recognizable γ rays is also high compared

OG9.2-12

Table I

Type of Event	Predicted Events/s	Observed Events/s
Gamma Ray pairs (1)	1.1	0.9
Upper Wall Events (2)	0.9	0.6
Scattered single tracks (3)	0.8	0.8
Other (4)	0.6	1.0

(1) Recognizable pairs. The prediction includes atmospheric γ rays and γ rays produced in the outer instrument shell.
(2) Tracks originating in the walls of the upper chamber.
(3) This number is generally consistent with the expected number of low energy Compton γ-rays plus pair production γ-rays for which one track is too short to meet the acceptance criteria.
(4) This category includes short single tracks, multiple single tracks, and events with little information.

to earlier balloon instruments. This favorable rate of useful events was predicted by the model based on the better active volume to wall ratio and to the improved directional recognition of the time-of-flight system. The similarity of this balloon instrument to the EGRET instrument and the known superior aspects of EGRET strongly suggest that EGRET will also have a high fraction of useful events.

d. Automatic Data Processing. The majority of the data for a high energy γ-ray telescope are the spark chamber pictures. A set of programs, originally developed for the SAS-2 instrument and since refined, analyze the event pictures by pattern recognition. These programs efficiently screen out pictures which do not contain useful information and identify the track structure of potential γ-ray events, such as the one shown in Fig. 2. Even though the information content of this instrument is low compared to other γ-ray telescopes, the results of the automatic analysis showed that this program works very well even here, both in selecting desired events and structuring them correctly.

4. Summary. The High Energy Gamma Ray Balloon Instrument has provided a flight test of an austere version of the EGRET telescope. The results have proven the instrument subsystems and approaches and have assisted in the development of assembly procedures used for EGRET.

5. Acknowledgements. We thank George Simpson and Bill Cruickshank for their valuable assistance in the early stages of the program. Our thanks go also to the National Scientific Balloon Facility, Palestine, Texas, for their flight support.

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MEASURED PERFORMANCE OF THE NEW UNIVERSITY OF CALIFORNIA GAMMA RAY TELESCOPE

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MEDIUM ENERGY COMPTON SCATTER TELESCOPE
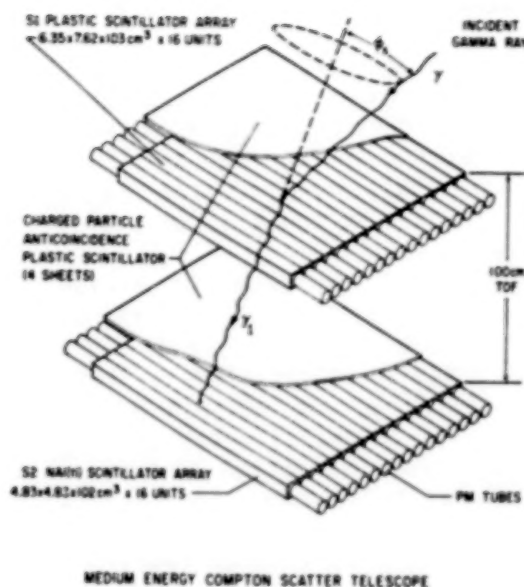
Figure 1

The design and expected performance of the new University of California medium energy balloon-borne gamma ray telescope shown in Figure 1 have been previously described (1,2). This telescope is sensitive to 1-30 MeV gamma rays. In this presentation the results of our initial calibration will be fully described. This will include the position and energy resolutions of 32 plastic and NaI(Tℓ) scintillator bars, each 100 cm long. The telescope's measured angular and energy resolutions as a function of incident angle will be compared with detailed Monte Carlo calculations at 1.37, 2.75 and 6.13 MeV. The expected resolutions are 5° FHWM and 8% at 2.75 MeV. The expected area-efficiency is 250 cm.

The telescope is now being prepared for a balloon flight in September, 1985.

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BURST AND TRANSIENT SOURCE EXPERIMENT (BATSE)
FOR THE GAMMA RAY OBSERVATORY (GRO)

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1. Introduction. The Burst and Transient Source Experi-
ment (BATSE) on the Gamma Ray Observatory (GRO) is expected
to provide new and better observational data on bursts to
test current and future models of burst sources. These data
will include: (1) the celestial distribution of hundreds of
burst sources over the life of the mission, (2) burst loca-
tions within several degrees, within 2 days after their
occurrence, (3) observations of weaker bursts and better
observations of short timescale fluctuations and spectral
variations, (4) observations by a single experiment over a
much larger energy range than previously available, and (5)
more sensitive measurements of the spectral features which
have been observed in many bursts. This paper briefly
describes the GRO mission, the BATSE instrumentation and the
burst observational capabilities. More comprehensive des-
criptions have previously been presented [1,2]. Two associ-
ated papers in this conference describe in more detail the
capabilities for spectral observations of gamma-ray bursts
[3] and capabilities for observations of other types of
discrete sources [4].

2. Instrumentation. BATSE is one of four experiments on the
GRO (Figure 1), a major shuttle-launched, free-flying obser-
vatory (to be launched in 1988). The spacecraft, one of the
heaviest to be launched by the shuttle, has a self-contained
propulsion system to enable the spacecraft to maintain a low
altitude (between 350 km and 450 km) for an extended period.
The capability to refuel the GRO from the shuttle can allow
mission durations considerably longer than the 2-year

nominal mission. The spacecraft is stabilized in three axes
and the primary instrument axis can point anywhere in the
sky with 0.5° accuracy and with 2 arcmin aspect. The com-
plete space-craft weighs over 15,000 kg and will occupy
about one-half of the shuttle payload bay.
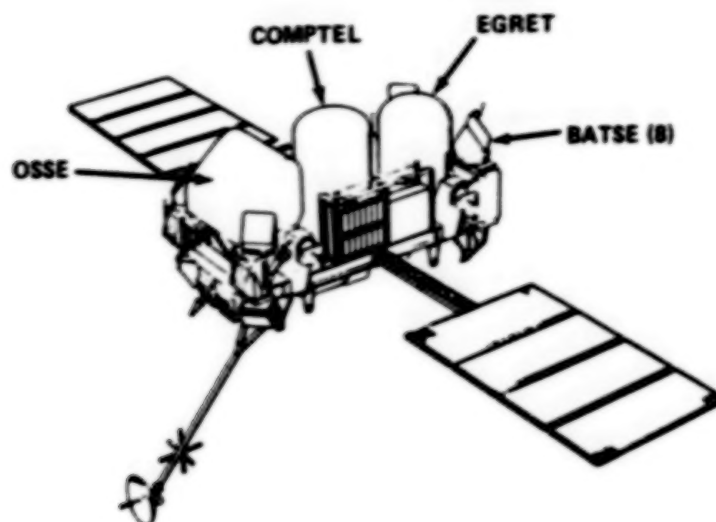
GAMMA RAY OBSERVATORY (GRO)

Figure 1

The BATSE experi-
ment is an all-sky gamma-
ray monitoring experiment
designed primarily for the
detection and detailed
study of gamma-ray bursts
and other transient high-
energy sources in the
energy range from 20 keV
to 10 MeV. Eight uncol-
limated detector modules
are positioned around the
spacecraft to provide an
unobstructed view of the
sky (see Figure 1). A
large-area, flat crystal
scintillation detector
provides a high sensitiv-
ity for weak bursts and
fine time structure
studies within stronger
bursts. A spectroscopy
scintillation detector is
included in each detector
module. This detector is
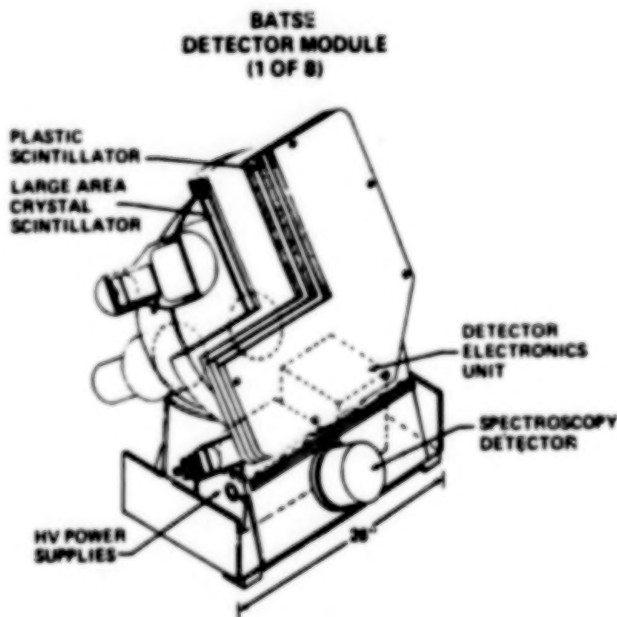
Figure 2

optimized to obtain better
energy resolution and to
cover a wider energy range
than the large-area detec-
tors. Figure 2 shows a
cut-away view of one of
the detector modules. Fig-
ures 3 and 4 show the
effective area and resolu-
tion of the BATSE detec-
tors. For sufficiently
strong bursts, temporal
fluctuations down to sev-
eral microseconds may be
detectable as well as
coarse spectral variations
on timescales as short as
10 ms. The location of
gamma-ray bursts to within
several degrees may be
determined using the rela-
tive responses of the
BATSE large area detectors
(2).

Scintillation
pulses from the detectors
are processed by two means
in each module. An array
of four fast discrimina-
tors can provide count
rates up to about 10^6 cps
with negligible dead-time.
A pulse height-to- time
converter simultaneously
provides spectral data on
each pulse. A gated base-
line restoration circuit
greatly reduces gain vari-
ations for counting rates
up to $\sim 2 \times 10^5$ cps. All
high voltage power sup-
plies for the PMT's are
independent and are pro-
programmable with 8-bit
resolution.

Data from all
sixteen detectors (eight
large-area and eight spec-
troscopy) are routed to a
central electronics unit
for digital processing by
special-purpose data boards
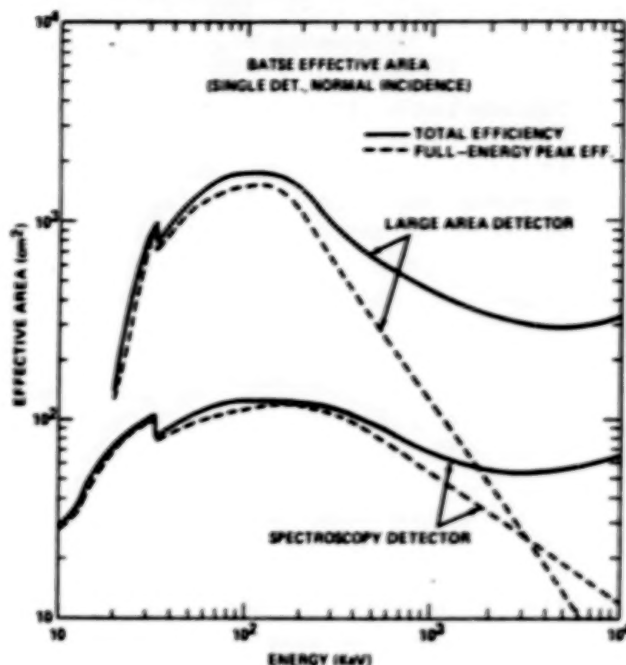
Figure 3
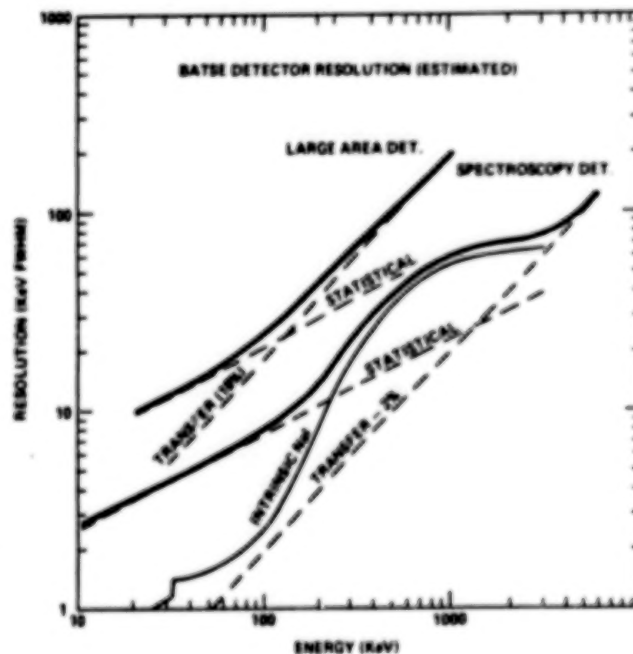
Figure 4

under the control of a microprocessor. Spectral 4 data are accumulated into 128 channels for the large-area detectors and 256 channels for the spectroscopy detectors. Twelve data types are available with different, programmable parameters to specify energy channel widths and temporal resolution [1,2]. The data system also contains a burst trigger system to detect and rapidly accumulate a large amount of data (~500 kB) for later playback through the GRO telemetry system. The burst trigger signal is sent to the other three instruments on the GRO, which also have capabilities for burst observations with their scintillation detectors.

The BATSE large area detectors, in addition to providing better single-spacecraft locations of gamma bursts than has been thus far possible, will permit observations of weaker gamma-bursts. An accurate Log N-Log S distribution can be measured over four decades in S (from $\sim 10^{-7}$ to 10^{-3} ergs/cm^2) during the GRO mission, as well as the celestial distribution of hundreds of bursts. Prior difficulties in the measurement and interpretation of Log N-Log S data[5] should be overcome by BATSE. The BATSE/ GRO experiment will also become an important component of the interplanetary burst timing network. The unprecedented sensitiv- ity of the BATSE detectors may also uncover new, unexpected char-acteristics of bursts and other transient high-energy objects.

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GAMMA-RAY BURST SPECTROSCOPY CAPABILITIES
OF THE BATSE/GRO EXPERIMENT   N85-34954

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ABSTRACT

A scintillation spectrometer is included in each of the
eight BATSE/GRO detector modules, resulting in all-sky
coverage for gamma-ray bursts. The scientific motivation,
design and capabilities of these spectrometers for
performing spectral observations over a wide range of
gamma-ray energies and burst intensities are described.

1. Introduction. In the past five years it has become clear on both
observational [1,2] and theoretical [3] grounds that the spectra of gamma-
ray bursts are rich sources of information which is crucial to determining
the nature of the burst phenomenon. The observations have revealed various
spectral components, most of which must arise in separate regions. A long-
lived component in the x-ray band may be the afterglow of the cooling burst
plasma [4]. A gamma-ray component from tens to hundreds of keV, the
classical burst emission, has an exponential form [5,6] and appears to be
due to some thermal process with a temperature of $^{\sim}10^9$ K. Above $^{\sim}500$ keV a
high energy gamma-ray component often extends to at least 6 MeV with an
approximate power law form [7] and has been observed up to 30 MeV in one
case [8]. In the 25-70 keV band unresolved absorption lines have been
observed in $^{\sim}30$ percent of the bursts and a few emission lines have also
been observed [5,6,9]. These have been interpreted as due to cyclotron
processes in terragauss fields, i.e. near a neutron star. At $^{\sim}400$ keV,
broad, marginally resolved emission lines with $^{\sim}200$ keV width have been
observed in $^{\sim}5$ percent of the bursts [5,6] and are interpreted as red-
shifted pair annihilation radiation. All these lines' narrow widths
require a cool, $T < 2 \times 10^9$K, region for their formaton. A narrow, $^{\sim}40$ keV
wide, emission line observed in one burst at $^{\sim}740$ keV is consistent with a
redshifted gamma-ray from the first excited state of ^{56}Fe [10] and implies
a temperature of $^{\sim} 2 \times 10^9$K. All of the components vary on time scales

shorter than the observations' integration times, which range from 0.25 sec to 5 seconds. In general, correlations among the components' variations have not been established. However, the annihilation line appears to be correlated with intensity on a 0.25 sec time scale in one well observed burst [11].

It is apparent that each region has its particular spectral signature which, in principle, can be independently followed with time-resolved spectroscopy over a broad energy band during a burst. Such observations would result in a new level of understanding of the evolution of the physical conditions of the various emission regions, their causal relationships, and their relationships to the underlying energy source of the burst. This is the primary motivation for the BATSE Spectroscopy Detectors, which are the subject of this paper. The very short cooling time scales near a neutron star, $<10^{-6}$ sec, imply that the spectral components are expected vary on the same time scale as the intensity. Thus sensitive spectral observations are required on short time scales, typically 0.1-1 sec, often as short as 10 msec and in one case, 5 March 1979, <0.2 msec.

2. Instrumentation. An overall description of the BATSE experiment is presented in an accompanying paper [12]. Each of the eight BATSE modules contains a 12.70 cm x 5.62 cm NaI(Tl) Spectroscopy Detector, which has an energy resolution of 7 percent at 662 keV and a Be window that extends its energy range down to 7 keV. (The effective area versus energy is shown in the accompanying paper.) The set of detectors has all-sky coverage and burst data are taken taken from the four detectors which most directly view a burst, resulting in an average sensitive detector area of ~ 500 cm^2. 14 keV to 10 MeV energy losses are analyzed into 2752 linear channels and then data compressed into 256 channels, preserving the detectors'energy resolution. An average event conversion cycle requires ~ 6μs, allowing a throughput of ~ 2x10^5/sec-det, which corresponds to a burst flux of ~ 2x10^{-4}erg/cm^2-sec. Discriminators at 7 keV, 20 MeV and 40 MeV provide data in the 7-14 keV, 10-20 MeV, 20-40 MeV and > 40 MeV bands. Linear operation at high counting rates is assured by 1) high current PMT bleeder strings which are zener diode regulated and 2) a gated baseline restorer in the analog electronics. It is planned to calibrate the nonlinear light output of the NaI(Tl) scintillators below 100 keV with the monochromatic x-ray beam at the Stanford Synchrotron Radiation Laboratory. Additional calibrations up to ~ 10 MeV will use radioactive sources and neutron capture gamma-rays.

The data are simultaneously stored in memories in two modes which are enabled by the BATSE burst trigger and preserve the detector IDs. In the HER (high energy resolution) mode, 192 spectra, including discriminator counts, are stored with a time resolution based on a time-to-spill algorithm that allows integrations as short as 64 msec at times of high rates and provides up to ~ 100 seconds of coverage with an average integration time of ~ 1 sec. Higher time resolution, for a subset of a burst's gamma-rays, is provided by the TTE (time-tagged events) mode, which stores 65,536 pulse heights, each time tagged to 128 μs precision. These data will provide a statistically significant spectrum measurement for each ~ 200 counts during source limited observations, e.g. each msec at a burst flux of ~ 5x10^{-5}erg/cm^2-sec. Part of the TTE memory acts as a

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OF POOR QUALITY

pre-trigger buffer and will capture the leading edge of a burst that preceeds the the burst trigger.

3. Background and Sensitivity. Since the detectors are unshielded, their background is dominated by gamma-rays of cosmic, spacecraft and atmospheric origin. Lines at 511 keV and several other energies due to detector radioactivity will not significantly affect the sensitivity and the 511 keV line will be used for energy calibration. The background rate above 20 keV will be ~ 2000 sec^{-1}. A burst with <E> = 100 keV and a flux of 2×10^{-6} erg/cm^2-sec would produce the same rate.

In order to estimate sensitivity, we assume a 5 second burst with the spectrum, $dN/dE = 1/E \exp(-E/250$ keV) plus an extension above 300 keV as an E^{-2} power law. Line strengths are expressed in units of fractional equivalent width, i.e. the usual equivalent width (keV) divided by the line centroid energy (keV). Figure 1a shows the sensitivity to unresolved lines. Data from various line observations [5,9,10] are plotted. These all have large equivalent widths and much weaker lines could be detected in the more intense bursts. The time required to detect a typical, 20 percent width line is shown in Figure 1b. During the most intense flux periods it
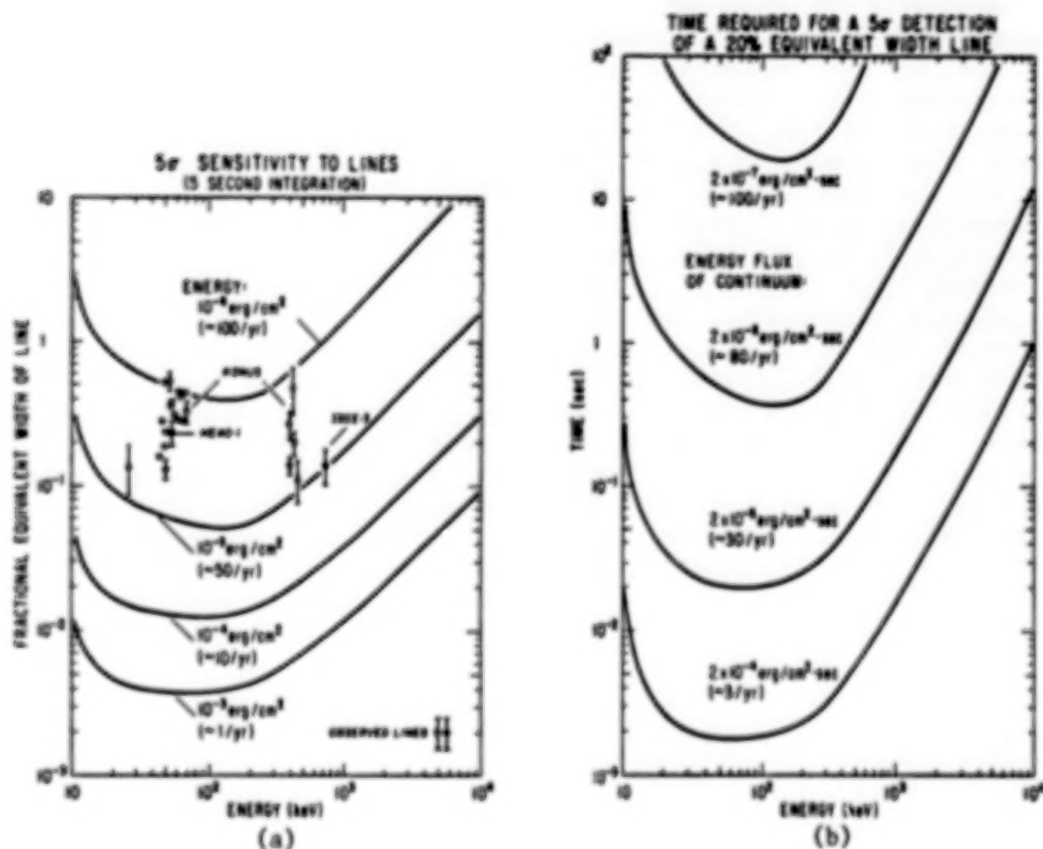

Figure 1. (a) – Sensitivity to spectral lines. (b) – Integration times required for line detection. The observations will be background limited at fluences (fluxes) below 10^{-5}erg/cm^2 (2×10^{-6}erg/cm^2-sec). The anticipated observed frequency of bursts above the indicated strength is given in parenthesis.

will be possible to obtain cyclotron and annihilation line measurements with few msec time resolution, while at low fluxes, i.e. ~ 10^{-6} erg/cm²-sec, ~ 1 sec time resolution will be possible. The search for nuclear lines in the ~ 1-10 MeV region will require longer integration times, from ~ 0.01 to 1 sec in the more intense bursts. Assuming 6 logarithmic energy channels per decade, 5σ measurements of the continuum spectrum would require half of the time indicated in Figure 1b.

4. Conclusion. The BATSE Spectroscopy Detectors have a powerful combination of energy band, sensitivity, and energy and time resolution, which represents a one to two orders of magnitude improvement over previous instruments. We can anticipate an equally large increase in our knowledge of gamma-ray bursts late in the decade when these detectors' observations become available.

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CAPABILITIES OF THE GRO/BATSE FOR MONITORING OF DISCRETE SOURCES

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ABSTRACT

Although the Burst and Transient Source Experiment (BATSE) to be
flown on the Gamma Ray Observatory has as its primary objective
the detection of gamma ray bursts, its uncollimated design will
enable it to serve a unique function as an all-sky monitor for
bright hard x-ray and low-energy gamma ray sources. Pulsating
sources may be detected by conventional techniques such as
summed-epoch and Fourier analyses. The BATSE will, in addition,
be able to use earth occultation in an unprecedented way to
monitor sufficiently bright sources as often as several times per
day over ~85% of the sky. We present estimates of the expected
BATSE sensitivity using both of these techniques.

I. INTRODUCTION

Various details of the design and expected performance of the BATSE
have been presented in previous papers [1-3]. Although the prime scientific
objective of this instrument is to detect and characterize gamma ray bursts,
the observation of other types of sources constitutes an important secondary
objective. The ability to act as a near-all-sky monitor for persistent and
longer-lived transient sources (by using earth occultation) and for long-
period pulsating sources (by the standard techniques such as epoch-folding,
Fourier analysis, etc.) is inherent in the instrument as designed for its
prime objective. The capability to detect short-period pulsars has been
incorporated by adding electronics hardware and software which performs on-
board epoch-folding. We report here the results of calculations of the
estimated BATSE sensitivity for observations using the epoch-folding and
earth-occultation techniques. These results apply only to the BATSE large
area detectors. Similar analyses of data from the spectroscopy detectors
may significantly improve the sensitivity in specific cases where a wider
energy range and/or finer energy resolution are of interest.

II. DETECTOR EFFICIENCY AND BACKGROUND ESTIMATES

The accuracy of the calculated sensitivity depends upon the reliability
of the estimates of a detector's efficiency and its expected background
properties. Estimates of the efficiency of a BATSE large area detector
which we used for this calculation have been derived analytically and are
presented in an accompanying paper at this conference [3]. The expected
background in orbit is the sum of three principal components: the diffuse
gamma ray sky background, the earth's atmospheric gamma ray albedo, and the

interactions of charged particles in the detector and surrounding material.
We have calculated the first component by convolving the diffuse background
spectrum with the estimated detector efficiency. The sum of the second and
third components was taken to be equal to the background of the detectors in
MSFC's balloon-borne instrument [4], which can be considered design
prototypes of the BATSE large area detectors.

III. SENSITIVITY USING THE OCCULTATION TECHNIQUE

Approximately 85% of the sky is occulted at some time during each GRO
orbit; the orbital precession of 7° per day ensures that any point in the
sky may be monitored at least once every two months with the occultation
technique. A sufficiently long-lived source will produce one or more steps
in the overall detector count rate corresponding to immersion into and/or
emersion from occultation by the earth. This is of interest not only for
monitoring the variability of persistent sources and long-lived transients,
but also for detecting transients on timescales of a few minutes to a few
days which are too long-lived and/or too weak to trigger the on-board burst
detection system. Although a few such events have been observed previously
[e. g., ref. 5], very little is known of their nature.

The time of occurrence of the occultation steps provides information on
the location of a transient. The accuracy of the source location will
depend somewhat on its intensity and its elevation above the orbit plane;
preliminary estimates indicate that an accuracy of ~0.5° should be typical.

Because of the wide field of view of the BATSE detectors, the variation
in background due to the difference in surface brightness between earth and
sky will occur on a much longer timescale than the occultation steps (which
last about 8 s for a source in the plane of the orbit). It is assumed that
other systematic background variations will also be negligible on the
occultation timescale, and that improvement of sensitivity by summation of
the occultation steps over many orbits will be feasible.

The sensitivity estimates were derived by assuming that the source
intensity at each step may be determined by taking the difference of two
60 s integrations, one while the source was unocculted and the other while
it was occulted. Table I shows the estimated sensitivity (relative to the
intensity of the Crab nebula) at 99.9% confidence for several different
energy ranges. The improvement obtained by multi-orbit summation is
evident. The practical upper limit to the number of orbits which may be
combined is presently unknown.

Table I. BATSE Occultation Sensitivity

Energy Range (keV)	99.9% confidence sensitivity (Crab units)		
	1 orbit (90 min.)	16 orbits (1 day)	224 orbits (2 weeks)
20-50	0.1	0.03	0.007
50-100	0.2	0.04	0.01
20-100	0.07	0.02	0.005
100-500	0.3	0.08	0.02

The most sensitive sky survey performed thus far at these energies used the UCSD/MIT A-4 instrument on HEAO-1 [6]. This instrument scanned the entire sky once every six months using fan-shaped fields of view, so that a given source was typically observable for several weeks at a time at six month intervals. In Table II we list the number of sources in the A-4 catalog which would be detected by BATSE in the 40-80 keV energy band for various timescales. It is interesting to note that the limiting sensitivity of the A-4 survey in this range is approximately the same as the BATSE sensitivity for a two-week orbit sum. Thus, the BATSE will be able to monitor all 40-80 keV sources in the A-4 catalog with two-week time resolution.

Table II. BATSE Sensitivity to HEAO A-4 Catalog Sources

40-80 keV (99.9% confidence)

Time Resolution	BATSE sensitivity (Crab units)	Number of HEAO A-4 sources
1 orbit (90 minutes)	0.1	5
16 orbits (1 day)	0.03	17
224 orbits (2 weeks)	0.009	46

IV. SENSITIVITY TO PULSATING SOURCES

Pulsating sources fall into two categories in the BATSE data, according to their pulse period. The first type have periods longer than ~10 s, so that the continuous readout of rates with 1.024 s or 2.048 s resolution may be used to search for both known and unknown periodicities. All-sky coverage is implicit, except during earth occultation. The second type, with shorter periods (down to a few ms), requires on-board folding and thus is possible only for known periodicities. The hardware limits on-board folding to two periods at a time, one using data from selected large area detectors and the other from selected spectroscopy detectors.

It has been assumed for the purpose of estimating sensitivity that pulsating sources will be detected by using the conventional epoch-folding technique. In addition to its dependence upon predicted detector efficiency and background, the time required to observe pulsations of a particular statistical significance using this method is dependent upon the shape of the pulse light curve. Table III shows the estimated sensitivity (99.9% confidence) relative to the pulsed flux of the Crab pulsar (assumed to be 0.027 ph/cm^2-s in the 30-100 keV range) for several values of the integration time and for three cases of pulse light curve: a sine-wave, the hard x-ray light curve of the Crab pulsar, and a rectangular pulse with 10% duty cycle.

Table III. BATSE Pulsar Sensitivity (30-100 keV)

| Integration length | 99.9% confidence pulsed sensitivity (Crab pulsar units) | | |
	Sine shape	Crab shape	Rectangular shape
1 orbit (90 minutes)	0.2	0.1	0.04
16 orbits (1 day)	0.04	0.02	0.01
224 orbits (2 weeks)	0.01	0.007	0.003

V. SUMMARY

Sensitivities attainable with the BATSE in observing non-burst sources have been estimated using assumptions appropriate to searches for known or suspected sources and presented in this paper. Except in the case of short-period pulsars (where on-board folding requires a priori knowledge of the approximate pulse period), it will also be possible to examine the BATSE data for previously unsuspected sources. In this latter case, efficient search procedures will most likely make use of other techniques such as Fourier analysis which have not been explicitly considered in our sensitivity estimates. Therefore, these estimates should be treated with some caution in applying them to generalized searches.

Finally, we show in Table IV the time required for BATSE to achieve 99.9% confidence measurements of typical high energy sources using the occultation technique and, where applicable, epoch-folding. It is clear that the successful application of these and similar techniques to the BATSE data will provide unprecedented and valuable sensitivity for near all-sky monitoring of low energy gamma ray sources.

Table IV. BATSE Sensitivity (30-100 keV) -- Selected Sources

Source name	Pulse Period (s)	Time required (99.9% conf. detection) Total emission (occultation)	Pulsed component (summed epoch)
A0535+26 (max.)	104	single step	single pulse
Centaurus A	N/A	single step	N/A
Crab pulsar	.033	single step •	1 minute
Vela X-1	283	single step	single pulse
Hercules X-1	1.24	6 hours	20 minutes
NGC 4151	N/A	1/2 day	N/A
3C273	N/A	2 days	N/A
A0535+26 (min.)	104	3 days	2 hours
MKN 509	N/A	2 weeks	N/A

• nebula plus pulsar

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LAPEX: A PHOSWICH BALLOON EXPERIMENT
FOR HARD X-RAY ASTRONOMY

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1. Introduction. Satellite and balloon observations have shown that several classes of celestial objects are hard (≥ 15 keV) X-ray emitters. A complete sky survey in the 15-180 keV energy band with a sensitivity of ~ 10 mCrab has been performed with the UCSD/MIT instrument (A4) on board the HEAO 1 satellite (1). About 70 X-ray sources were detected, including galactic and extragalactic objects. Hard X-ray emission has been detected in the Galaxy from X-ray pulsars, black hole candidates, transient X-ray sources, burst sources. Extragalactic sources of hard X-ray emission include clusters of galaxies, QSOs, BL Lac objects, Seyfert galaxies.

While the few brightest hard X-ray sources are well studied, much additional observational work is required to obtain spectral and temporal information in the 20-200 keV band from sources with flux levels in the range 1-10 mCrab (10^{-6} - 10^{-5} photons/cm^{2}s keV).

Another open issue is the identification of the hard X-ray sources with objects known at lower X-ray energies or at optical wavelengths. As the HEAO 1-A4 sky survey results have shown, the central galactic plane region ($|b^{II}| < 10°$, $260 < l^{II} < 50°$) is crowded with many hard X-ray sources, which were not resolved with the $1.5° \times 20°$ crossed collimators of the HEAO 1-A4 detectors. These crowded sky fields require observations with better angular resolution.

Future satellite missions like SAX (Italy) and XTE (U.S.A.), which have as primary objectives the observation of hard (15-200 keV) X-ray sources at sensitivity levels of about one order of magnitude better than the A4 experiment, are yet at their early study phases. Their field of view of $1°$ FWHM will not make it possible to resolve all of the crowded fields. Therefore selected sky fields can be profitably studied with balloon observations that have limiting sensitivities of about 1 mCrab in the 20-200 keV energy band and angular resolutions better than $1°$.

In this framework, we are developing a Large Area Phoswich Experiment (LAPEX), which meets the above-mentioned requirements. It has:
i. a broad energy band of operation (20-300 keV);
ii. a 3 σ sensitivity of about 1 mCrab in 10^4 s of live observing time;
iii. imaging capabilities with an angular resolution of about 20'.

The first balloon flight of the LAPEX is scheduled for 1986.

2: Experiment Description. We report here the essential characteristics of the experiment. A detailed technical description of the entire payload has already been given (2) and an experiment summary is found in Table 1. The detection plane is an array of 16 scintillator detectors. Each detector is made of a 145 x 145 mm^2 NaI(Tl) crystal 6 mm thick, which is sandwiched with a CsI(Na) crystal having the same frontal surface and a thickness of 50 mm. The scintillations of both crystals are viewed by a photomultiplier tube (PMT) of diameter 5" through a light guide of lead glass 15 mm thick. Each group of 4 detection units is surrounded by a NE110 plastic scintillator, exclusive of the aperture. A passive graded shield (Pb, Sn, Cu) is inserted between the crystals and the lateral plastic scintillator. A bank of four passive collimators is mounted above each group of four detection units. The collimators are made of electroformed hexagonal tubes of lead (0.1 mm) surrounded by Tin (0.25 mm) and Copper (.08 mm) on both sides. The collimators cause a 9% reduction of the total geometric area. Each collimator bank is mounted so as to obtain a triangular response with a flat top of 20'. Each collimator bank can rock by 8°, indipendently of the other three, at a desired frequency.

Table 1
Experiment summary

Energy range of operation	20-300 keV
Total geometric area	3400 cm^2
Energy resolution ($\Delta E/E$) at 60 keV	17% (FWHM)
Field of view	3° (FWHM)
Angular resolution	20' (FWHM)
Time resolution	100 μs
Spectral bin width	~ 1 keV
Telescope mounting	alt-azimuthal
Post-facto attitude reconstruction	3'
Guiding system	automatic, from ground station

Above the rocking collimators one can mount a set of 16 rotating modulation collimators (RMC), one for each detection unit, in a configuration that makes the instrument a true imaging device. Through a proper choice of the distance between the grid planes of each RMC it is possible to image a sky field with an angular resolution that depends on the minimun pitch-angle (angular distance between planes of maximum transmission). A description of this multi-pitch rotation modulation collimator (MPMC) can be found in refs. 2 and 3. For our experiment we have chosen 8 different distances between grid planes, a minimum pitch-angle of 40', grid planes made of tungsten strips with 1.5 x 1.5 mm^2 square section, and a rotation period of 100 s. The MPMC will operate in the 20-200 keV band.

An active gain control system will allow a continuous monitoring of the instrument gain and, if required, to adjust it to a preselected value. The gain control is based on the use of ^{241}Am sources deposited into plastic scintillators placed at the bottom of the rocking collimators.

The α particles associated with the ^{241}Am X-rays give a signal in the plastic which allows to tag the X-ray events, therefore to measure the detector gain at 60 keV and, if required, to change the PMT high voltage.

An absolute calibration of the detection plane is also available and this is based on the use of ^{139}Ce sources which scan the field of view every 2000 s.

3. Observation strategy and expected performances. The instrument will operate with either the rocking collimators or the MPMC. In the first case the observation strategy of the celestial objects is to point in turn two banks of collimators in the source direction and the other two towards an empty field. The banks are swopped between ON and OFF positions at a selected frequency. We have carefully evaluated various systematic errors in the background subtraction due to this rocking technique, e.g. background variations due to variations of exposed area, atmospheric thickness and telescope zenith angle. We have found that the systematic errors can be controlled within 0.3%. As a consequence, we expect to be able to measure source fluxes as low as 1% of the background at a significance level of 3 σ. The expected background count rate is based on an in-flight test (4). Figure 1 shows the expected spectrum determination sensitivity of the instrument when it will operate with the rocking collimators. We plan to use rocking collimators to study isolated sources.
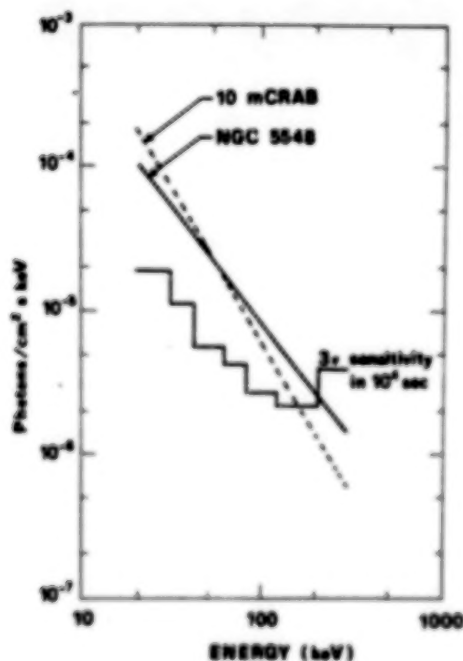

Fig. 1. – Spectrum determination sensitivity of the instrument with the rocking collimators

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The MPMC will be mounted to resolve complex fields. When the instrument is used in this configuration the flux sensitivity will be lower (by a factor of ~ 3), but the angular resolution will be at least 20' FWHM. As an example, Fig. 2 shows the expected image in the 20-200 keV band of two X-ray sources 1° apart, one 0.5 Crab and the other 0.3 Crab, for an observing time of 100 s. Computer simulations have shown that the multi-pitch approach is superior to the classical RMC configuration, specially in case of crowded fields.

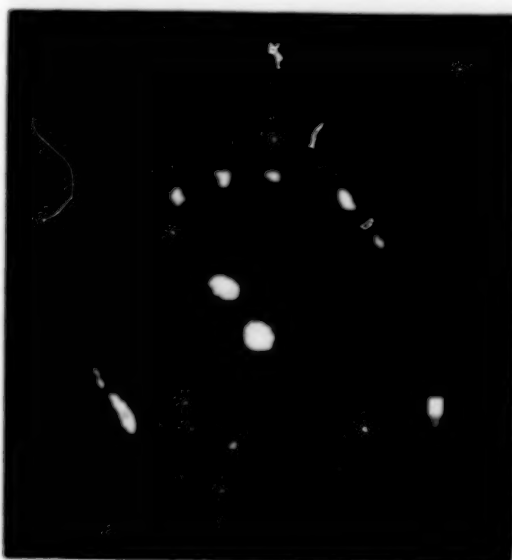Fig. 2. - Imaging capability of the instrument with the MPMC. This image was obtained simulating a field with two X-ray sources 1° apart of comparable intensity (see text).

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AN IMPROVED TIME OF FLIGHT GAMMA-RAY TELESCOPE TO MONITOR DIFFUSE GAMMA-RAY IN THE ENERGY RANGE 5 MeV - 50 MeV

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Abstract

A time of flight measuring device is the basic triggering system of most
of the medium and high energy gamma-ray telescopes. A simple gamma-ray
telescope has been built in order to check in flight conditions the
functionning of an advanced time of flight system. The technical ratings
of the system will be described. This telescope has been flown twice with
stratospheric balloons, its axis being oriented at various zenital
directions. The results of these flights for what concern : diffuse
gamma-rays, atmospheric secondaries, and various causes of noise in the 5
MeV-50 MeV energy range will be presented.

1. Introduction and motivation.   Gamma ray telescopes for energies in
excess of 10 MeV are mostly built around a track chamber in which photons
are materialized by pair effect. Coordinates of track of an event is read
if the veto counter above and on the sides of the chamber have not been
triggered and if downward moving particles (supposed to be electrons)
issuing from the bottom trigger a set of thin counters in coïncidence see
(1) (2). This last set of two counters is usually named "time of flight"
measurement since its purpose is to measure sense and duration of travel
of the electrons across it and also to give a limit to the angular
aperture of the telescope.

Nevertheless once looking at the tracks visually or with the help of some
track identifying software one is left with only a few percent of "good
events" among the initial trigger rate of the chamber. This fact leading
to a waste of telemetry bit rate.

A second fact is the large number of upward moving events giving tracks
stopping in the chamber or reflected backward and simulating pairs /1/.
These events if not properly removed by the time of flight counters
(T.O.F.) can plague the data. In order to improve the characteristics of
a gamma-ray telescope designed for the energy range 5 MeV-50 MeV (3)
(AGATHE experiment) we have undertaken to built a T.O.F. telescope with
the double objective to improve its capabilities on a short T.O.F. path
(57.5cm) but with realistic lateral dimensions (80x40cm) keeping in view
to reduce the total dimensions of the telescope. In a second step we
included this T.O.F. in a very simple gamma ray telescope and had it
flown with a stratospheric balloon in order to monitor and try to explain
various counting rate observed in balloon borne gamma ray experiments.

2. Description.   The experimental set-up used in flight is shown fig. 1.
It includes from the top :
1. An anticoïncidence counter plastic scintillator NE 102A with
dimensions 85x45x1 cm.

2. A Tantalum target 0.03 cm thick the same thickness used in the Agathe telescope spark-chamber.

3. T.O.F. counters made of two sheets of NE 102A plastic scintillators with dimensions 80x40x0.5 cm placed at 57.5 cm separation.

4. We had at the bottom a 10 cm thick plastic scintillator calorimeter (85x45x10cm) made of Altustipe blue 155 manufactured by Altutor. This scintillator was used in various electrons beam for other purposes and proved to be linear far electrons up to 24 MeV for the 10 cm thickness. Photomultipliers were XP2020 for the AC and T.O.F., and XP 2041 for the calorimeter.

NIM electronic units were used for the fast electronics and ADC, and home made electronic circuits for housekeeping informations and interfacing with telemetry . The whole telescope could be rotated in flight at various zenit angles and stabilized in azimut. Basic events were defined by AC+S1+S2 and T.O.F. value in a 50nsec window. The functionning of the T.O.F. measurement is based on the comparison with a Time to Amplitude Converter of the mean arrival time in S1 (upper T.O.F. counter) and S2 (lower T.O.F. counter). These mean arrival times on each counter were obtained by sending left and right signals in a very performing "Time Pick-off"circuit made by Schlumberger-Enertec and then both signals from the T.P.O. output in a "mean-timer" Lecroy.

The informations sent by telemetry were

- T.O.F. observed in the 50 nsec window, with 256 channels accuracy. The width of the window and the delay in S2 allowing to display upward and downward moving particles.

- Amplitudes in T.O.F. counter S1 and S2 obtained by mixing dynodes signal from left and right PM tubes and digitized in 256 channel ADC.

- Amplitude read in the calorimeter digitized in 256 channel the muon peak beeing in the channel 118.

3. Results.   Fig.2 shows the T.O.F. spectra obtained at ceiling (4mb) for 0° zenit direction   in AC ON and AC OFF configuration.

- T.O.F. spectrum : The first and second peak being respectively upward and downward moving events are very clearly separated when using particles see AC OFF   at celing Fig. 2 a small displacement of the peaks toward greater time difference at ceiling can be explained by a much larger isotropy of arrival direction. When looking at gamma-ray T.O.F. (AC ON configuration) the separation is not so good and is probably due to the fact that pair of particles are reaching the lower T.O.F. counter at spatial distance not so negligible for the mean-timer compensation to be efficient. Nevertheless distinction between the two senses of travel is still very good and can be made of the order of 10^{-3} at the expense of a small loss of good events. Another noticeable fact that can be observed on the T.O.F. distribution AC ON is the great number of upward moving events a fact also noted with Double Compton Telescope although using very different thickness of material and neutral events selection. (5)

- Calorimeter. The spectra obtained for gamma-ray events (AC ON) at various zenit angle have been used with the efficiency curve for gamma-ray obtained by Monte Carlo computation to derive the atmospheric gamma-ray spectrum above 9MeV in these directions.